OPTIMIZED REGENERATIVE BRAKING TECHNOLOGY FOR ELECTRIC BIKES

By

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ABSTRACT

Regenerative braking is an effective approach for electric vehicles to extend their efficiency. It is the emerging technology used on hybrid gas/electric automobiles to recoup some of the energy lost during stopping. Regenerative braking has to be carried out together with the conventional barking. In brake system design for electric vehicles, the basic equation must be concerned, one is properly applying braking force to quickly reduce the vehicle speed and meanwhile maintain the vehicle traveling direction stable and controllable through the steering wheel on various road conditions and also recovering the braking energy as much as possible in order to improve the energy utilization efficiently. The regenerated energy is saved in a storage battery and used later to power the motor. Regenerative braking takes energy normally wasted during braking and turns it into usable energy. It does improve energy efficiency of the vehicle. In this work, a mathematical model of a regenerative braking system for the braking efficiency has been developed. The experimental results are compared with the simulated results. The electricity generated by the battery during braking varies accordingly to the speed of the vehicle. So to utilize the generated electricity completely a suitable Electronic Control Unit is designed.

Keywords: Braking, Kinetic Energy, Heat, Motor, Generator, Voltage Generated, Discharge Rate.

INTRODUCTION

Regenerative braking is an effective approach for electric vehicles to extend their efficiency. A few investigations have been made for regenerative braking and braking force distribution of electric vehicles [1, 2, 3, and 4]. It is the emerging technology used on hybrid gas/electric automobiles to recoup some of the energy lost during stopping. Regenerative braking has to be carried out together with the conventional braking. In brake system design for EVs, the basic equation must be concerned [5]. This energy is saved in a storage battery and used later to power the motor. Electric motors and electric generators are essentially two sides of the same technology.

1. Regenerative Braking System

In Regenerative Braking system, as the driver applies the brakes through a conventional pedal, the power supply to the electric motors is stopped. By this action, the motor stops propelling the vehicle but due to the forward momentum the vehicle moves for some distance and then eventually stops the vehicle [6].

Whenever the electric motor shaft is rotated (mechanical energy is given to the motor), it becomes an electric generator or dynamo [7 and 8]. This generated electricity is fed into a chemical storage battery and used later to power the car at city speeds. Regenerative braking takes energy normally wasted during braking and turns it into usable energy. Thus it improves energy efficiency of the electric vehicle.

2. Design Aspect

The objective of this work is to implement the Regenerative Braking technology in electric vehicles particularly in Electric bikes. The first phase of the work is to develop a mathematical model and to simulate it using MATLAB/SIMULINK. A bike was selected for demonstration of Regenerative braking and the second phase is to implement the Regenerative Braking System in bike. A bike is selected for demonstration of Regenerative braking and also an ECU has been developed for optimization of the battery charging (Figure 1).

3. Electric Vehicle Conversion

- A vehicle that is light and aerodynamic in order to maximize distance traveled per battery charge is selected. There must be also an adequate room to load motor and batteries.
- The battery pack, which provides a source of electrical power. The most commonly available and affordable batteries are lead acid flooded type.
- The D.C motor that propels the vehicle is mounted on the bike chassis. (Figure 3).
- Electric motor shaft (Driving shaft) is mechanically attached to the driveline system by a flange specially designed for this purpose (Figure 4).
- The power controller, which regulates the flow of energy between the battery and the electric motor is controlled by an electronic throttle.
- The charging circuit through which the regenerated energy is fed to the battery is placed between the motor and the batteries.
- A contact breaker is used to change modes namely driving and charging modes. (Figure 5).

3.1 Motor Selection

The Motor is selected by studying the various characteristics curves of motor and also by calculating the

- Maximum RPM that motor should have.
- Voltage that can be generated for the Maximum RPM.

If, V_{max} is max velocity of the bike

N_{max} is max speed of prime mover (motor)

g is Output driven to input driver ratio

r is effective wheel radius

$$\frac{N_{max}}{V_{max}} = 2.65\frac{g}{r} \text{ [Max speed of e-bike = 45kmph]}$$

Maximum RPM of the motor, $N_{max} = \left(\frac{2.65gVmax}{r}\right)$

Voltage generated, $V = \frac{p\varphi\, ZNmax}{60A}$

Φ = Flux / pole in weber.

Z = Total number of armature conductors

P = Number of poles

A = number of parallel paths (= 2)

N = Speed of armature in rpm (N_{max} of motor)

3.2 Model of Transmission System

$\omega_m(t) = \frac{\gamma * v(t)}{r_w}$	ω_w	Wheel angular velocity (rad/sec)
	r_w	Wheel radius (m)
$\tau_m(t) = \frac{\tau_w(t)}{\gamma}$	γ	Gear ratio
	v(t)	Vehicle Speed (kmph)
	τ_w	Wheel torque (Nm)
$\omega_m = \omega_w(t) * \gamma$	τ_m	Motor torque (Nm)

- The speed of the prime move is taken in angular speed but for easy calculation it is taken in terms of RPM itself and the simplified relation is used below.
- Direct drive is given from the prime mover (i.e.) from motor to the wheels through a single constant ratio (Figure 2).

Model Calculation of gear ratio:

$$\frac{\omega_m(t)}{v(t)} = \frac{\gamma}{r_w}$$

N is max speed of motor

$$\omega_m = 2\pi N$$

$$\frac{N}{v(t)} = 2.65\frac{\gamma}{r_w}$$

$$\gamma = \frac{N^* r_w}{v(t)^* 2.65}$$

From the Project specifications,

N = 1200 rpm, r_w = 0.31 m, v (t) = 45 kmph

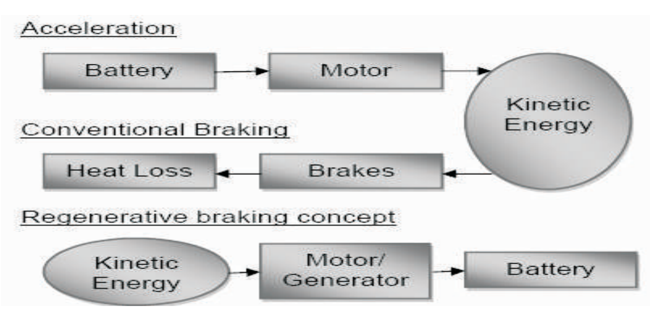

Figure 1. Energy Flow Overview

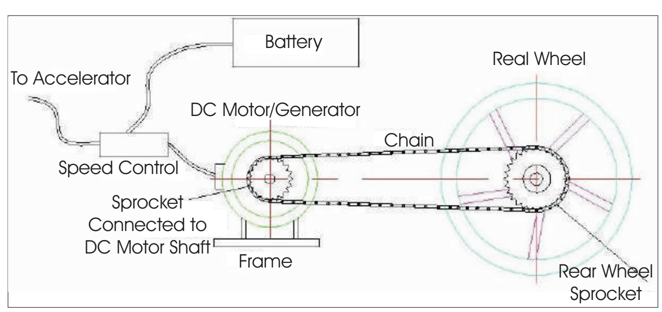

Figure 2. Model of Transmission System

$$\gamma = \frac{1200*0.31}{45*2.65}$$

$$Y = 2.93$$

T_W= no. of teeth in Wheel sprocket. (18 teeth)

T_M= no. of teeth in motor output shaft

$$\gamma = (T_W / T_M)$$

$$T_M = (T_W / \gamma)$$

Figure 3. Experimental setup for RBS

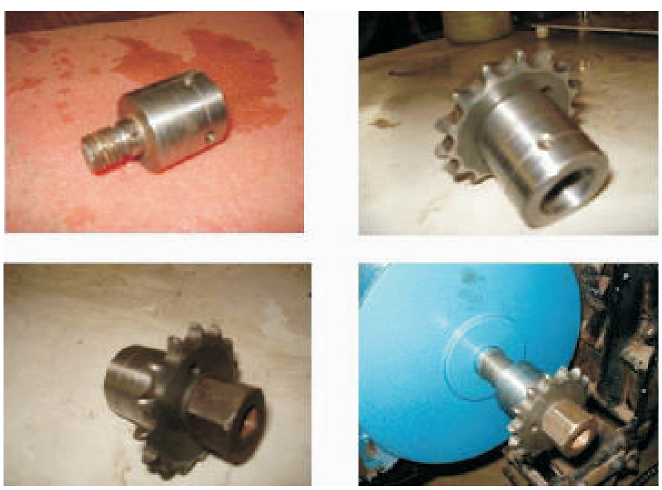

Figure 4. Flange that connects motor shaft and driveline system

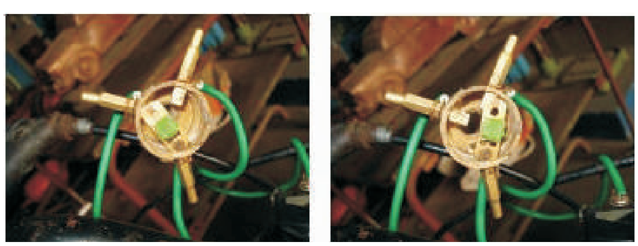

Figure 5. Contact breaker in driving and charging position

$$= (41/2.93)$$

= 14 teeth (approx.)

Thus the output Sprocket of the motor should have 14 teeth to achieve maximum speed of 45kmph.

4. Experimental Setup

The experimental setup designed for the demonstration of regenerative braking in Electric bike is shown below.

4.1 Working

In Regenerative Braking Technology, when the brakes are applied through a conventional lever, the current flow to the motor from the battery is stopped. Since there is no flow of current, the electric motor stops running thus stopping the bike. This regenerative braking is a mild brake which is due to the counter torque generated by the motor when it is converted to generator (Figure 6).

Whenever the brake is applied, electric current supplied to the motor from the battery is cut down. Now the vehicle moves because of its forward momentum. Thus it rotates the motor and it act as a generator. Due to this, an emf is induced in the generator leading to the generation of electric current. This generated electricity is fed into a chemical storage battery and used later to power the bike at city speeds.

The circuit works in two modes

- Driving Mode
- Charging mode

4.2 Driving Circuit

The driving circuirt consists of the terminals of the primover connected to the battery through a ON/OFF switch and a potential switch (Figure 7). These two switches are connected from the positive terminal connection of the

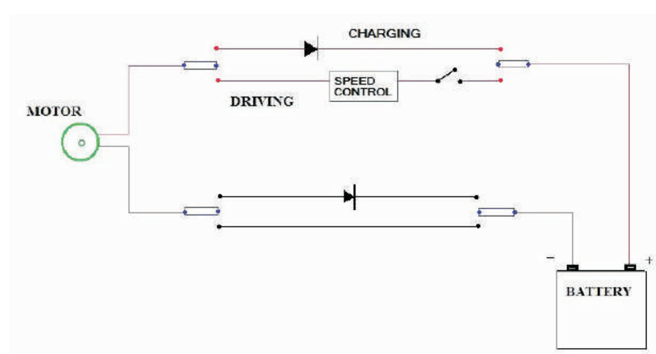

Figure 6. Working of RBS

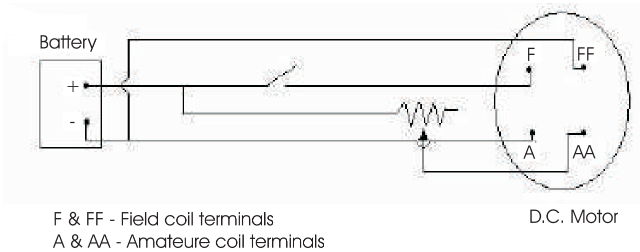

Figure 7. Driving circuit for RBS

battery. Potential switch is a component that controls the speed of the motor.

4.3 Charging Circuit

The charging circuit has the diode which prevents the flow of current from battery to the motor due the reverse biased condition of diode (Figure 8). During generation mode the power from the generator is stored to a capacitor due to forward biased condition of diodes and it charges the battery. The electronic control unit for charging circuit is as given in Figure 9.

The layout for the optimized charging is shown in Figure 10.

5. Mathematical Equations Governing Regenerative Braking System

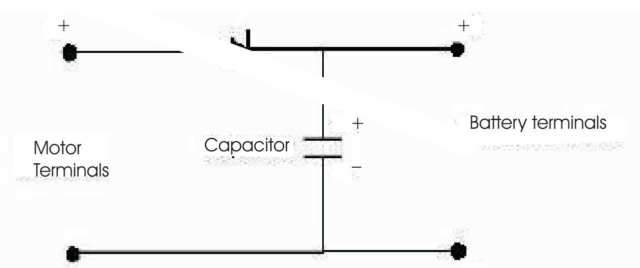

Figure 8. Charging circuit for RBS

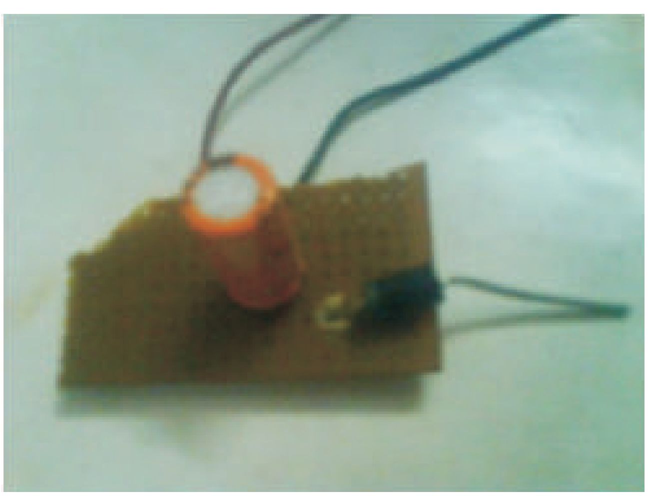

Figure 9. Electronic Control Unit for charging circuit

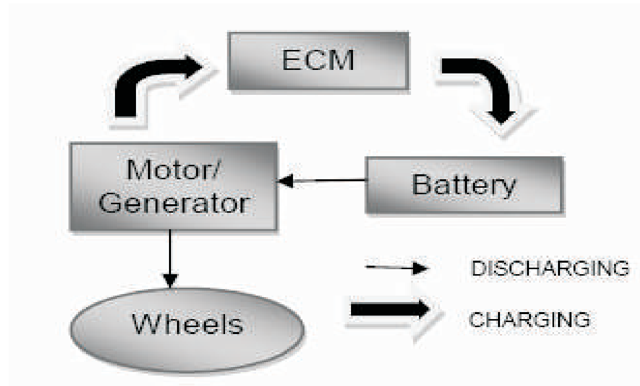

Figure 10. Layout for optimized charging

5.1 Efficiency Of The Regenerative Braking System

Drag force Fd - $(\frac{1}{2})C_d\rho AV^2$, [1]

C_d = Vehicle aerodynamic drag coefficient

ρ = Air density, Kg/m^3

A = Vehicle frontal area, m^2

V = Vehicle velocity, m/sec

Rolling resistance, $Fr = MgC_r$ [2]

M = Vehicle test mass, Kg

g = Acceleration due to gravity, m/sec2

C_r = Rolling resistance coefficient

Acceleration force, $Fa = Ma$ [3]

M = Vehicle test mass, Kg

a = Vehicle acceleration, m/sec2

Total power needed to propel the vehicle,

$P = (F_d + F_r + F_a)V$ [4]

Total energy required, $E = \int P\,dt$

Case (i) when a ≥0 (vehicle is accelerating)

$E_w = \int P_t\,dt$

E_w = Energy output at the driving wheels

P_t = Power at instantaneous time t

$E_1 = E_w / \eta 1$

E_1 = Energy input to the power train

η_1 = Overall efficiency of the power train system

Case (ii) when a ≤0 & P ≥0 (vehicle slows down or braking)

Battery is still supplying energy to maintain the vehicle velocity

$E_w = \int Pt\, dt$

E_w = Energy output at the driving wheels

P_t = Power at instantaneous time t

$E_1 = E_w / \eta 1$

E_1 = Energy input to the power train

η_1 = Overall efficiency of the power train system

When a ≤0 & P ≤0, the regenerative braking is activated.

Vehicle kinetic energy is converted to electrical energy which is returning to the battery.

$E_r = - \int Pt\, dt$

$E_2 = E_r / \eta_2$

Where E_r = Energy regenerated

E_2 = Energy returned to the electric storage system

η_2 = Overall efficiency of the regenerative system

E_2 / E_1 express the percent of regenerative energy returning to the vehicle electric storage system.

E_1 expresses the energy consumption of the vehicle without regenerative braking system.

5.2 Conversion of Kinetic Energy Into Useful Work

U = initial velocity

V = final velocity

W= Weight of the vehicle

F = retardation

t = braking time or stopping time

$g = 9.8\ m/s^2$

By Newton's equations of motion,

$V = u - ft$ [Once brake is applied V=0]

$f = u/t$

$V^2 = U^2 - 2fs$

$U^2 = 2fs$

Stopping distance, $S = \frac{U^2}{2f}$ [5]

Braking force, $F = \left(\frac{W}{gf}\right)$ [6]

(When the vehicle moves on a level road)

Work done = Braking force x Distance moved

Work done = Heat generated

Heat generated $= \left(\frac{W}{g}\right) f \times \frac{U^2}{2f}$

$= \frac{1}{2}\left(\frac{W}{g}\right)U^2$

$= \frac{1}{2} mu^2$

Heat Generated = Kinetic Energy

The power required to slow the vehicle is in general,

Power $= \frac{\text{workdone}}{\text{timetaken}}$ = kinetic energy / time taken

Work done = Kinetic Energy

But here, it is calculated by

P_{wh} = vehicle velocity * Driving force

$= \nu * F_T$ [7]

5.3 Studies from Mathematical Equations

- In this study 2 cases are taken under considerations one is with Braking time 5 sec and other is with 3 sec.
- In the second case the vehicle comes to halt in shorter distance than the former case because more braking force is needed and it is applied in the later case.
- To bring the vehicle to rest from a velocity say 30 kmph, the heat generated in the brake pads or shoes is same in all the conditions with respect to braking time and deceleration rate.
- To achieve the shortest stopping distance say in case II (i.e.) 12.48 m can be achieved in case I (i.e.) for the braking time of 5 s , only when this difference in braking force 24.09 N is provided by some source other than driver's effort.
- This additional effort is provided by the COUNTER TORQUE developed by the motor during braking. So the stopping distance can be reduced from the calculated values (Table 1).

5.3.1 Results of the Study

The heat generated is independent of braking time (i.e.)

	I	II
Breaking time t (s)	5	3
Initial velocity, u (kmph)	30	30
Final Velocity,v (kmph)	0	0
Deceleration, f(m/s^2)	1.67	2.78
Stopping Distance, S(m)	20.78	12.48
Braking Force, F_b (N)	391	486
Heat Generated	8124.9	8110.3

Table 1. Calculated values of Mathematical Equations Governing Regenerative Breaking System under two cases

how long the brakes may be applied the kinetic energy wasted is constant.

Regenerative Braking system can reduce the stopping distance considerably than the conventional systems.

6. Experiments Conducted

The electric bike is tested for its battery discharge rate. The vehicle was run on the chassis dynamometer to measure the battery discharge rate by subjecting it to numerous frictional brakes at various speeds. Then the regenerative braking system is used and similar tests are conducted to find the improved performance in the battery discharge time (Figure 11).

Also using the chassis dynamometer, the voltage generated at various speeds and the stopping distances are measured. Finally the efficiency of regenerative braking technology is calculated from the recorded values and the following characteristic curves are drawn.

- Vehicle speed vs Voltage generated
- Vehicle speed vs Regeneration period
- Vehicle speed vs Deceleration
- Vehicle speed vs Battery discharge rate

6.1 Voltage Generated For Various Vehicle Speed

The D.C motor is tested without any load to find its generated voltage at various speeds and the readings are tabulated. Then the motor is fitted in the bike for applying regenerative braking system in it and tested in the chassis dynamometer and the graph is plotted for generated voltage at various speed of the bike and it is shown in Figure 12.

Figure 11. Testing the E-bike on chassis dynamometer

From the result, it is inferred that the amount of voltage generated at low speed is less when compared to that of higher speed of the vehicle. As the speed of the vehicle increases, the generated voltage also increases and it is very high at the maximum speed of the bike.

6.2 Stopping time (regeneration Period) and Deceleration of the Vehicle for Various Vehicle Speed

The bike is driven at various speeds on the chassis dynamometer and their respective stopping time or regeneration period are measured by applying the regenerative braking i.e by cutting down the supply to the motor. The deceleration of the vehicle is calculated for each stopping distance and the graphs are drawn in Figures 13 & 14.

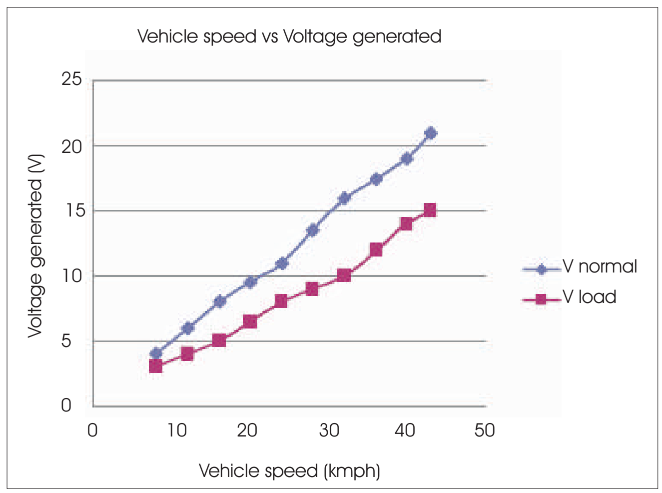

Figure 12. Voltage generated for various vehicle speed

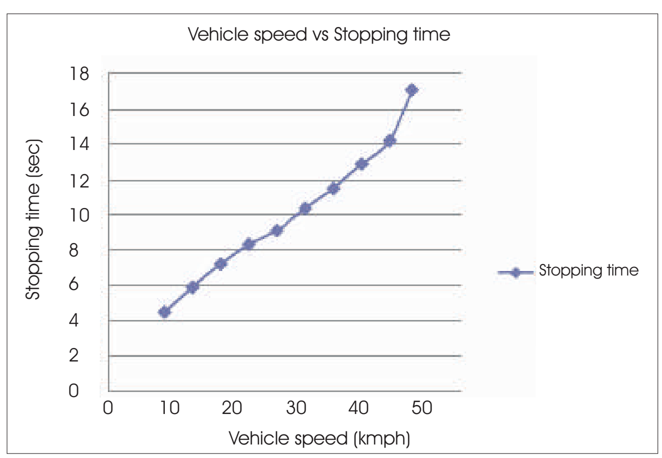

Figure 13. Variation of stopping time (regeneration period) with vehicle speed

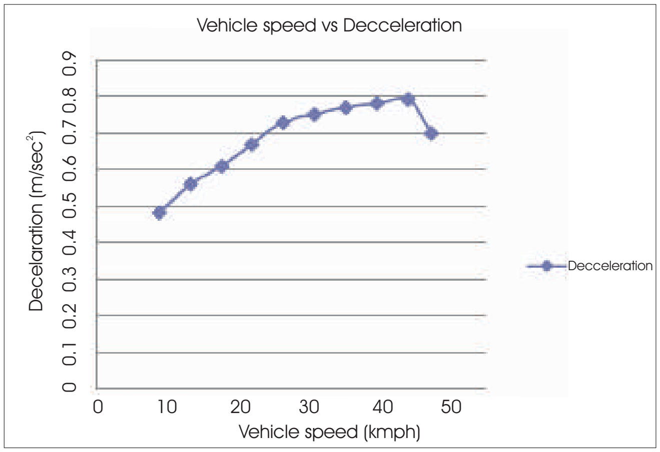

Figure 14. Deceleration of the vehicle with vehicle speed

The stopping time or regeneration period increase with the increase in the vehicle speed. The bike takes more time to stop at higher speeds when compared to lower speeds. This is because the velocity of the vehicle will be higher at high speeds.

6.3 Battery Discharge Rate for Various Speeds with and Without RBS

The vehicle is driven for various speeds on the chassis dynamometer. First the bike is driven without RBS by applying numerous brakes during operating period. Then the bike is driven with RBS by subjecting it to the same number of braking (Regenerative braking). The battery discharge rate is measured for both the cases. The graphs are shown in Figure 15.

Battery discharge rate is maximum at high speed of the vehicle and as the speed of the vehicle decreases the discharge rate also decreases. With the application of regenerative braking technology, there is a significant improvement in the battery discharge rate.

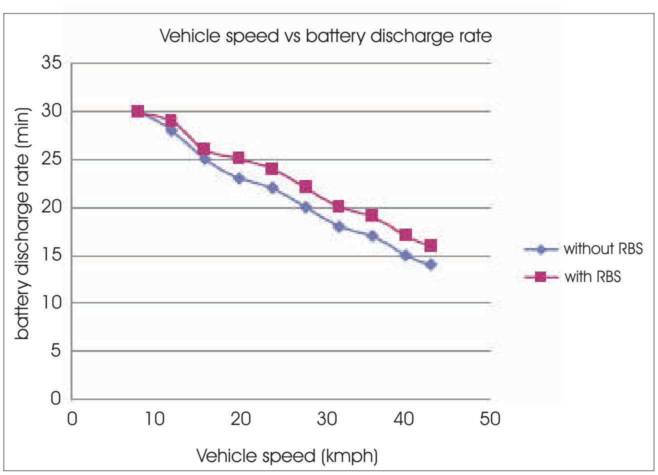

Figure 15. Comparison of Battery discharge rate for various speed with and without RBS

6.4 Calculation of Efficiency

The improved average efficiency for the discharging time of the battery in both cases (with and without RBS) with respect to speed is calculated as follows.

$$\eta = \left(\frac{T_{RBS} - T_{Normal}}{T_{Normal}} \right) X\ 100$$

T_{RBS} = Time for discharge rate with RBS
T_{Normal} = Time for discharge rate without RBS

Average calculated efficiency of the electric bike with regenerative braking system with respect to the speed is 9.05%

7. Conclusion

From the results, it is found out that the voltage generated at high speeds is more and the battery discharge rate is improved by Regenerative braking. The efficiency of the battery is increased by 9.05% and it is further increased twice in sloppy areas. Also, an ECU has been developed to utilize the voltage whole generated through RBS to charge the battery. Moreover when applying regenerative concept, the accompanying friction (electrical resistance) assists the normal brake pads in overcoming inertia and helps slow the vehicle.

8. Simulation in MATLAB

8.1 Variation of voltage generated with vehicle speed

From the result, it is found that the generation of voltage is high at high speeds. So, the efficiency of regenerative braking is more at high speed than at the low speed. To improve the efficiency of the bike at low speed, an ECU is developed for optimized charging (Figure 16).

8.2 Variation of discharge time of the battery With vehicle speed

From the Figure 17, it is inferred that the discharge time of the battery decreases as the speed of the bike increases. It is because the flow of current to the motor is more at high speed than at the lower speed.

9. Advantages

- Acts as secondary braking system thereby reducing

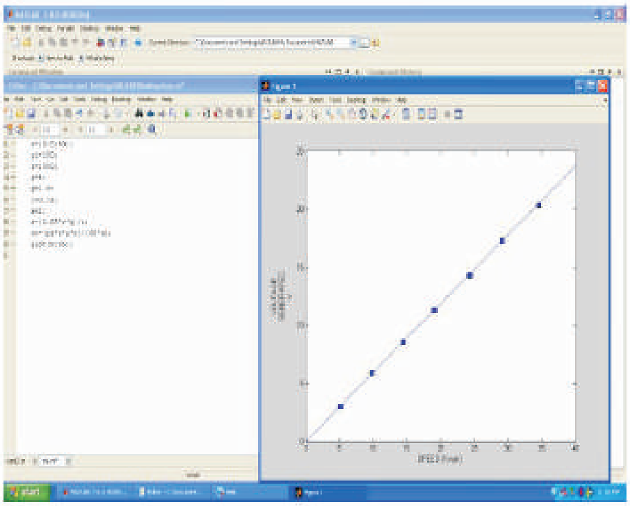

Figure16. Simulation of Voltage generated

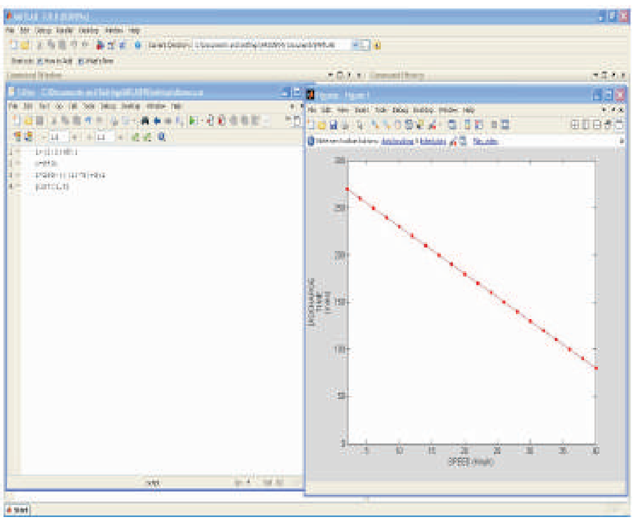

Figure 17. Simulation of Discharge time of the battery

the braking effort and increases safety.

- The battery discharge is very less or sometimes nil depending on the efficiency of regeneration.
- The advantages of regenerative braking are clear-cut as effectively drivers can enjoy 'something for nothing'.
- For electric vehicles, the time for recharging the batteries is considerably reduced.
- Increases the life of the Brake Pads.
- Size of the batteries could be reduced if regenerative technique is used for the vehicle.
- Highly effective in hilly areas and slopes.

10. Limitations

1. The main issue with regenerative braking is that it still relies on friction braking too.

2. Consequently the friction brake is still necessary to bring the vehicle to a complete halt.

3. Efficiency of Regenerative braking at lower speed is less.

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Abbreviations

EVs	Electric vehicles
RBS	Regenerative Braking System
D.C	Direct Current
h.p	Horse Power
rpm	Revolution per Minute
V	Voltage
I	Current
T	Temperature
A, amps	Ampere
AH	Ampere Hour
ECU	Electronic Control Unit

ABOUT THE AUTHORS

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