

## Design & Development of Regenerative Braking System at Rear Axle

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### Abstract

In this work, a new methodology with external generator is developed for regenerative braking system. Experimental test setup is developed to verify the feasibility of new methodology. Results are verified using Matlab Simulink simulation. About 10 to 12% of battery energy can be regenerated and stored into battery which shows 10 to 12% increase in Electric vehicles mileage.

**Keywords:** Regenerative brake, motor/generator unit, Matlab simulink.

### I. INTRODUCTION

Regenerative Braking System is the way of slowing vehicle by using the motors as brakes. Instead of the surplus energy of the vehicle being wasted as unwanted heat, the motors act as generators and return some of it to the overhead wires as electricity. This energy is stored in a large battery, and used by an electric motor that provides motive force to the wheels. The regenerative braking taking place on the vehicle is a way to obtain more efficiency; instead of converting kinetic energy to thermal energy through frictional braking, the vehicle can convert a good fraction of its kinetic energy back into charge in the battery, using the same principle as an alternator.

### II. MAXIMUM BRAKING FORCE REQUIRED

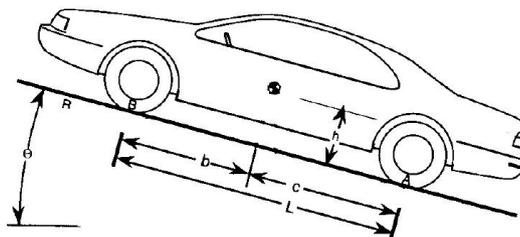


Figure.2.1. Vehicle length parameters

During braking, a dynamic load transfer from the rear to the front axle occur such that the load on an axle is the static plus the dynamic load transfer contributions. Thus for a deceleration,  $D_x$ , on each axle the maximum brake force is given by,

$$F_{xmf} = \mu_p W_f = \mu_p \left[ \frac{c}{L} W + \frac{h}{L} \frac{W}{g} D_x \right] \quad \dots\dots(1)$$

$$F_{xmr} = \mu_p W_r = \mu_p \left[ \frac{b}{L} W - \frac{h}{L} \frac{W}{g} D_x \right] \quad \dots\dots(2)$$

Where,

- $\mu_p$  = Peak coefficient of friction,
- $F_{xmf}$  = Maximum brake force on front axle,
- $F_{xmr}$  = Maximum brake force on rear axle

In this work, regenerative braking system is to be installed on rear axle. Hence, for designing the rear axle braking system, we must know the maximum braking force required on rear axle and this can be found out from equation (2), hence maximum rear braking force,

$$F_{xmr} = \mu_p W_r = \mu_p \left[ \frac{b}{L} W - \frac{h}{L} \frac{W}{g} D_x \right]$$

$$F_{xmr} = 0.3 \left[ \frac{1.058}{2.258} \times 1250 \times 9.81 - \frac{0.3}{2.258} \times 1250 \times 0.93 \right]$$

$$F_{xmr} = 1677.37 \text{ N}$$

Hence maximum braking force required at rear axle is 1677.37 N. This force is to be supplied by combination of regenerative braking system and disc brakes at wheel disc brakes. Considering that, we are going to design brake system parameters.

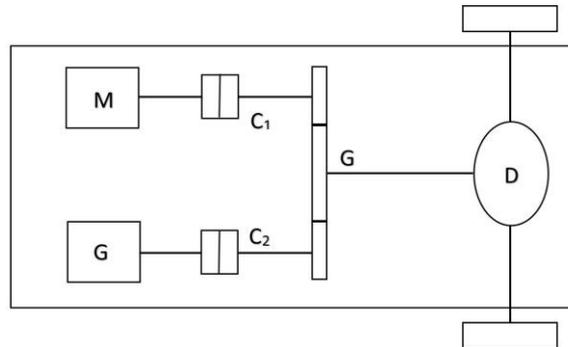
The brake system is to be so designed that the **regenerative braking system will be providing 30% of braking force required** and friction brake will be providing remaining braking force.

### III. LAYOUT OF THE VEHICLE WITH REGENERATIVE BRAKING SYSTEM AT REAR AXLE

The proposed layout is as shown in figure 3. The shaft connecting motor to differential, in case of non-regenerative braking EV, is split by gearing unit (G) having gear ratio, 3. The two small gears of gearing unit are provided with motor (M) and D.C. generator (G) at their respective ends through clutches C1 and C2.

In normal driving condition, clutch C1 is in normally driving condition. This supplies

driving torque from motor through gearing unit to the vehicle axle.

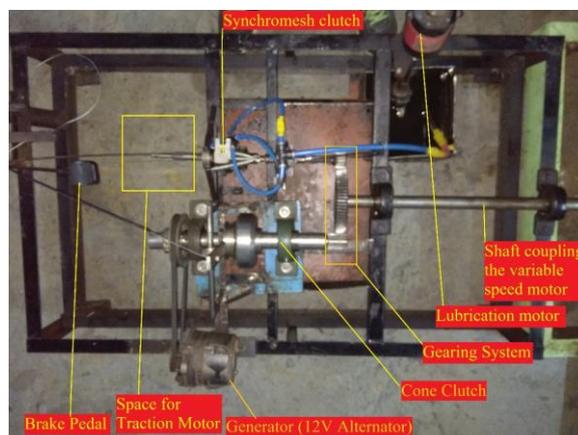


**Figure.3.1.** Layout of proposed Regenerative system

When brake is applied by driver, the clutch C1 disengages and C2 engages simultaneously. Then the torque is supplied in opposite direction, from wheels to the generator (G). This causes the generator (G) to convert mechanical energy to electrical energy, which is then supplied to battery pack through voltage regulator.

#### IV. DEVELOPMENT OF EXPERIMENTAL PROTOTYPE, EXPERIMENTAL TESTING AND MATHEMATICAL SIMULATION

The experimentation setup is built to verify the feasibility of regenerative braking system designed. The traction motor (M) and the generator (G) are connected in parallel to each with gearing arrangement. The bigger gear is keyed to the shaft of overall length 800mm, which is connected to the variable speed motor through rubber coupling. The gear ratio of gearing arrangement is kept 4.25.

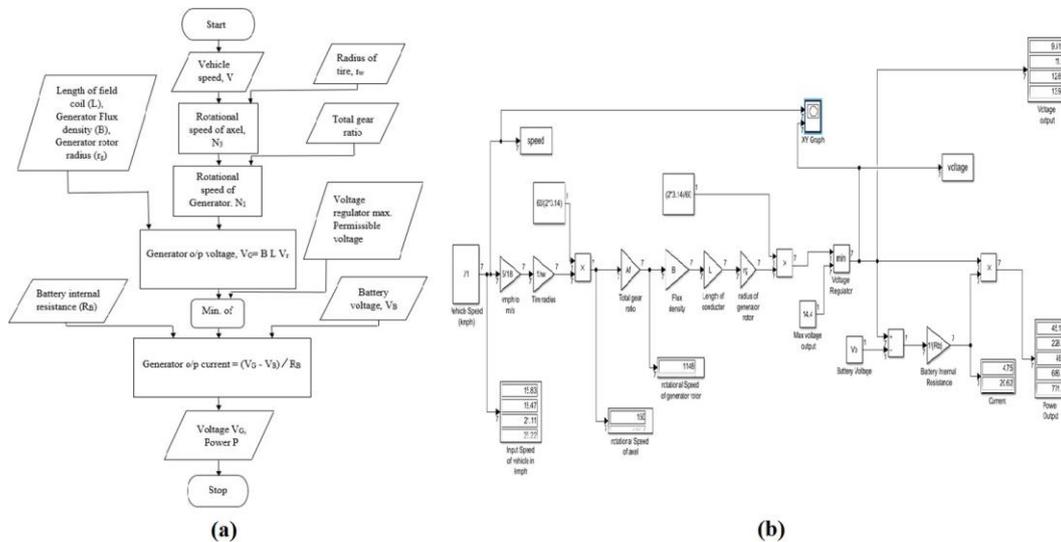


**Figure.4.1.** Actual Experimental Setup

The cone clutch is installed between the smaller gear and generator and synchronesh

clutch is installed between smaller gear and motor space. The generator is coupled to the shaft through belt and pulley arrangement having gear speed ratio 1.8. Hence the overall speed ratio between variable speed motor and generator becomes 7.65 (4.25×1.8). The synchromesh clutch is normally in closed condition. It can be opened/disengaged by sliding the sleeve by dog key which is operated by brake pedal though cable. The cone clutch is operated by using the vertical lever which is again connected to the brake pedal. The regenerative mechanism is so designed so that it works as explained above. When brake pedal is pressed the synchromesh gearing disengages and cone clutch is engaged simultaneously.

**Simulation In Matlab Simulink**



**Figure.4.2 (a) Flowchart for simulation (b) Simulation in Simulink (Matlab).**

Mathematical model is built in Matlab Simulink. The input is variable speed of vehicle and output of simulation is voltage and power output of generator.

- Solver = Ode5 (Dormand Prince)
- Solver Type = Fixed Step
- Fixed step Size = 0.001

Subsystems are used to calculate rotational speed at different stages of RBS, output voltage, output current and output voltage of generator. Other several blocks are used here such as gain, integration, constant, and multiple. Vehicle speed is the input to the simulation model and output is energy recovered which goes back to battery pack

## V. RESULTS AND DISCUSSION

### Experimental Results

The battery voltage recorded prior to testing was 9.04 volts, i.e. battery was not fully charged. This was recommended for testing otherwise it could not be possible to observe whether the battery was getting charged or not.

The rpm of the motor can directly be related to the speed of vehicle. Motor rpm was considered as rotational speed of the vehicle's wheels. Hence, the expected vehicle speed can be found out from these test results. Which is considered as input for simulation in Simulink.

**Table.5.1.** Experimental readings

Sr. No.	RPM before brake pedal pressed	RPM after brake pedal pressed	Voltage output
1	150	141	9.34
2	175	159	11.88
3	200	178	12.81
4	225	196	13.91
5	250	224	14.49
6	300	281	14.49
7	400	382	14.49

The wheel radius is considered to be  $r_w = 0.280$  m. Hence, vehicles expected speed for 150rpm motor speed will be,

$$V = \frac{2 \pi N}{60} r_w \times \frac{18}{5}$$

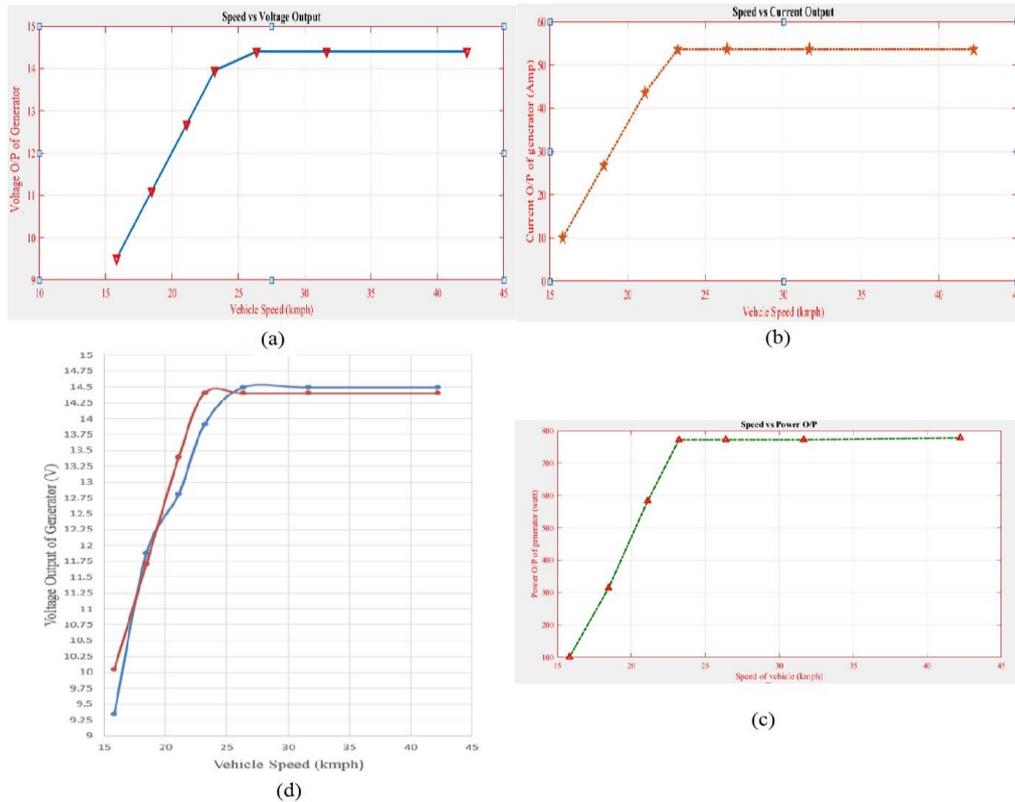
$$V_1 = \frac{2 \pi \times 150}{60} \times 0.28 \times \frac{18}{5}$$

$$V_1 = 15.83 \text{ km/hr}$$

**Table.5.2.** Modified experimental results

Sr. No.	Expected Vehicle Speed, (kmph)	Voltage output
1	15.83	9.34
2	18.47	11.88
3	21.11	12.81
4	23.22	13.91
5	26.38	14.49
6	31.66	14.49
7	42.22	14.49

## Simulink Results



**Figure.4.3** (a) vehicle Speed vs Voltage output trend, (b) vehicle Speed vs current output trend, (c) vehicle Speed vs Power output trend, (d) comparison between experimental and simulation results

The mathematical model gives directly the power output of generator on entering the vehicle speed as input. The figure --- shows the comparison between the expected results given by mathematical modelling and the actual results obtained from the test rig. The experimental results obtained are slightly differ from the theoretical results. Though voltage difference is not considerable at this point but when power output is to be considered, there will be larger difference. But comparing it will be within 10% error.

The graph shows voltage reading obtained are on lower side than expected. This is caused due to the transmission losses occurred in in gearing system and the losses occurring in alternator itself. But the overall error is within limit.

## Discussion on Results

The light weight electric vehicle battery pack is generally comprises of four individual 12V batteries are connected in series so as to obtain 48V output voltage.

The normally used battery pack for e-rickshaw is 48V 100AmpHr. The energy stored in battery after full charge is,

$$E_b = 48 \times 100 \times 3600 = 17280000 \text{ J} = 17280 \text{ KJ} \quad \dots\dots(1)$$

The energy recovered by RBS per second is 770 J (i.e. 770W). Considering that the regenerative brake is applied for 10 min (it may be more than 10min) during full use of the battery charging.

Hence the min energy recovered during one battery cycle,

$$E_{r1} = 770 \times 10 \times 60 = 462000 \text{ J} = 462 \text{ KJ} \quad \dots\dots(2)$$

Here, in this experimentation setup, we used the 12V alternator as generator, because there were limitations of cost of special purpose generator installation. If 48 V generator is used in place of 12 V generator, the output power will be four times of 12 V alternator, say all other variables remain constant.

Hence, Power output of 48V generator will be,

This shows, energy recovered is 1848 KJ.

Hence, the percentage energy recovered using Regenerative braking system will be,

From equation (1) and (3),

$$E_r = 462 \times 4 = 1848 \text{ KJ}$$

This, shows that minimum 11% battery energy can be recovered using the regenerative braking system which would otherwise be wasted to heat in friction brakes. Hence the distance travelled between two successive charging requirements can be increase to 10 to 15 % using this regenerative braking, when installed in actual vehicle.

Hence, the Regenerative braking system designed is successfully tested for its feasibility.

## V. CONCLUSION

The regenerative braking system used in the vehicles satisfies the purpose of saving a part of the energy lost during braking.

The regenerative braking system is designed to partially recover the battery charge wasted in braking of the vehicle. The energy is converted into heat by friction brakes which is dissipated to the environment. This Energy is utilized to rotate the rotor of generator converting mechanical energy of wheels into useful charge of battery.

The regenerative braking system cannot be used as main braking system of vehicle as it cannot bring the vehicle to rest.

Experimentation shows that minimum 11% battery energy can be recovered using the

regenerative braking system which would otherwise be wasted to heat in friction brakes. Hence the distance travelled between two successive charging requirements can be increase to 10 to 15 % using this regenerative braking, when installed in actual vehicle.

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