ENERGY STUDY OF REGENERATIVE BRAKING OF E-RICKSHAWS USING BRUSHLESS DC MOTORS

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Abstract: E-Rickshaws took the streets of Delhi by storm. The savings in fuel and cost attracted many but their limited range impacted the earnings of the average driver. Regenerative braking technology can harvest otherwise wasted energy and extend the range of electric vehicles (EV's). Regenerative Braking technology not only increases the range of EVs but also provides quieter braking with comparatively less wear to the mechanical brakes.

This paper will study the energy that can be harvested from a regenerative braking set up. Our testing apparatus will be described in detail along with the standard configuration of E-Rickshaws. With the mathematical model developed in this paper, an increase in range of up to 21% is observed.

1. INTRODUCTION

With rising environment awareness and rising prices of Diesel and Petrol, EVs and CNG converted vehicles are becoming more popular. The maintenance and operation of EVs along with their low operational cost are a big benefit to consumers but range and charge times are big problems. To keep production costs low, E-Ricks in India use Lead-Acid batteries over newer technology like Li-Ion and Ni-Cd. On top of the inconvenience of leaking batteries and regular acid top-ups, low recharging cycles along with depleting capacity over time are a big hinderance to the complete switch over to electric vehicles.

Regenerative braking systems convert the kinetic energy of the moving EV into electrical energy using their brushless DC motor as a generator. Using the principle of Electromagnetic Induction, when the kinetic energy of the EV causes it to coast, a voltage potential is developed across the ends of the 3 phases. However, due to Lenz's law (Conservation of energy), the motor resists this change in flux by exerting a torque on the wheels in the direction opposing their rotational motion. This causes the EV to come to a stop while generating electricity in the process.

A pure electric vehicle, PEV, has three main components. A battery pack, a motor controller and a motor. The motor could be a brushless direct current motor (BLDCM), an induction motor (IM) or switch reluctance machines (SRM). In E-Rickshaws, the most common motor is the BLDCM. Along with its simple construction, high efficiency, high speed range, high starting torque and noiseless operation, it simplifies the external electronics needed to add regenerative braking to any off the shelf E-Rickshaw.

2. REGENERATIVE BRAKING SYSTEM FOR E-RICKSHAWS

2.1 Standard configuration of an E-Rickshaw

4 inverter batteries are used at 24v each to power the EV. A half-bridge three-phase voltage source converter (VoSC) is used to control the 3-phase BLDCM. Most E-Rickshaws use a throttle handlebar for speed control and a foot pedal that mechanically controls a hub break in the wheels. This mechanical break pedal also pulls on a brake switch which is used to shut off the motor control to ensure the driver cannot accidentally accelerate and brake at the same time. This brake switch is an extremely vital component in our modular regenerative brake prototype. This switch is used to control the relays which connect and disconnect the 3 phases of the motor from the VoSC and the regenerative brake setup. E-Rickshaws use 2 hall sensors. One is in the throttle control to measure the angle of extensions. The other is in the BLDC to act as an encoder. The VoSC functions as the brain of the EV and uses a Proportional Integral and

Derivative control system to match the angle of extension of the throttle with the speed of the vehicle. This is also used to display the speed on the odometer.

Figure 1: Functional block diagram of E-Rickshaw configuration.

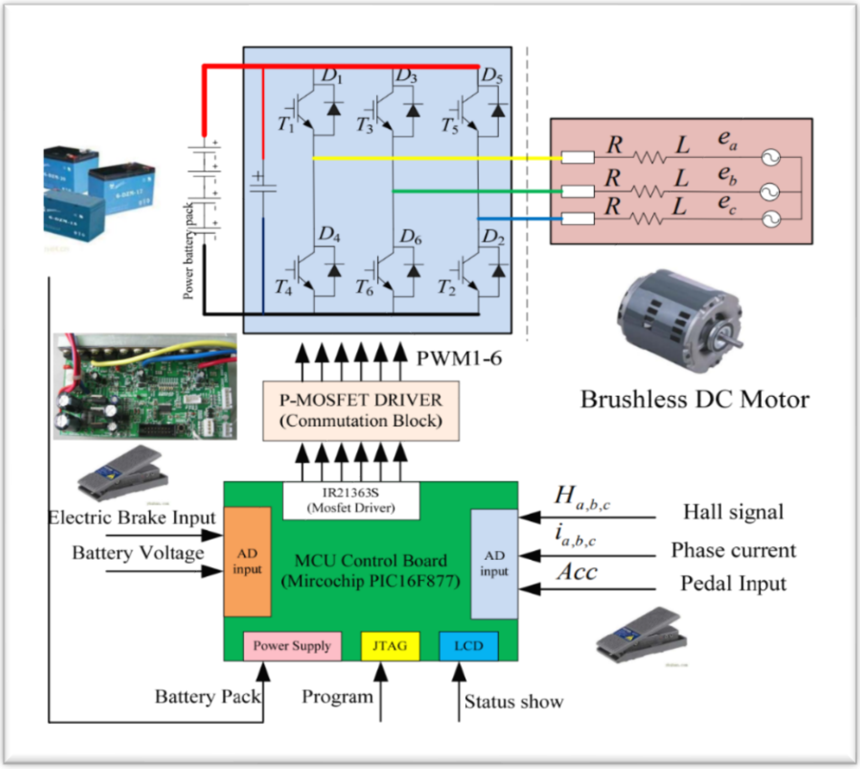


Diagram [5]

2.2 Working principle of regenerative braking

The mechanical braking process uses brake pads to increase the friction of the wheels and converts the kinetic energy of the moving EV into heat – causing the EV to slow down. The more current that is drawn, the faster the motor will slow to a stop. This however is too slow to be a primary braking system and most EVs incorporate a mechanical brake with a regenerative brake. In this paper, I will be focusing on the *maximum* amount of energy that can be recovered using a regenerative system. In all our tests no mechanical brakes were used, and the vehicle was allowed to coast to a stop.

When the motor is being powered by the VoSC, the 3 phases of the BLDC generate magnetic fields of changing polarity to cause continuous rotation in the armature. When the kinetic energy of the EV causes the wheels to freely spin, the magnets of the armature create a changing magnetic flux at the ends of the 3 phases, inducing current in them. Due to Lenz's Law (Conservation of Energy), the current is in such a direction that it opposes the magnetic movements that caused it, resulting in a torque on the armature that opposes the direction of rotation.

Mathematical representation of Faradays law of electromagnetic induction where ε = electromotive force and ϕ_B = electromagnetic flux.

$$\varepsilon = -\frac{d\phi_B}{dt}$$

In the equation above, the minus (-) sign denotes the direction of the induced current by Lenz's Law.

Figure 2: 3 pairs of power MOSFETs arranged in a bridge to provide sequential and alternating magnetic fields to the 3 phases.

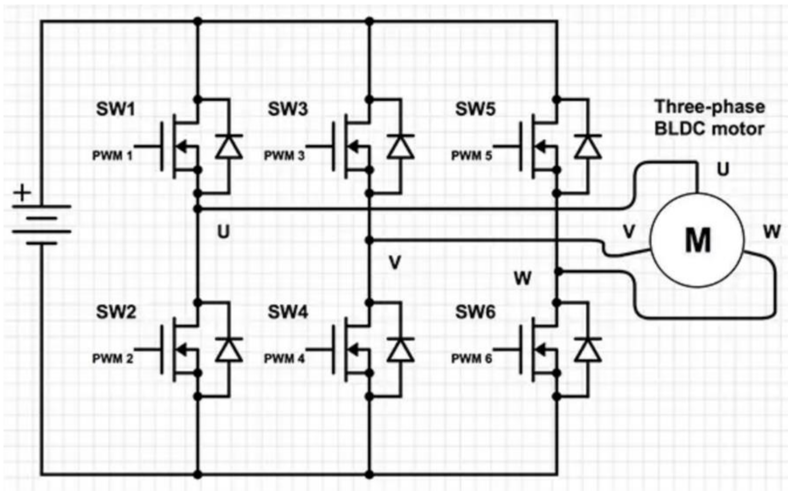
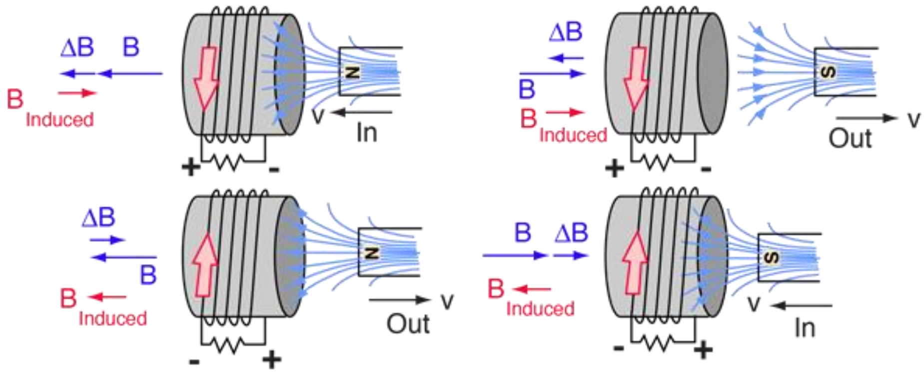


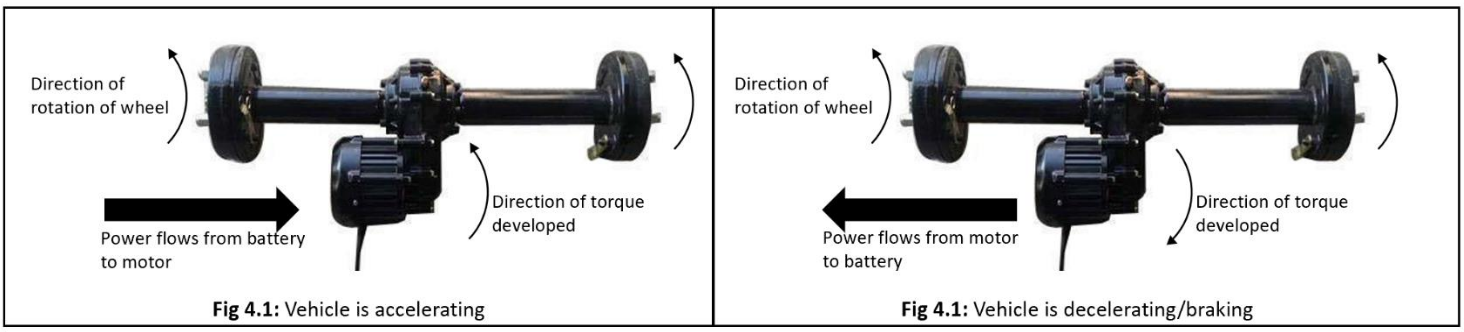
Diagram [8]

Figure 3: Lenz's Law states *"the current induced in a circuit due to a change or a motion in a magnetic field is so directed as to oppose the change in flux and to exert a mechanical force opposing the motion."*



Graphics [7]

Figure 4: Direction of power flow in two modes of operation. [4]



Graphics [6]

2.3 Mathematical Model of a Coasting EV

I modelled the routes for energy dissipation of the initial kinetic energy (2.3.1) of the EV. These routes are air resistance (2.3.2) and rolling resistance (2.3.3).

Here, the simplifying assumptions made are – (i) the vehicle is on flat ground and (ii) the vehicle undergoes constant deceleration.

2.3.4 details the amount of energy available and converting force terms into work done by integrating from 0 to T (total time elapsed).

2.3.1 Initial Kinetic Energy of the EV

The initial kinetic energy of the vehicle was easily found by $K = \frac{1}{2}mv^2$ where K = Kinetic energy of the EV, m = mass of the EV and v = velocity of the EV.

The weight of an un-loaded E-Rickshaw is 320kg. The vehicle has a rated capacity of 1+4, 1 driver with 4 passengers. However, the most common use of these vehicles in 1+2 capacity over short distances. The average weight of an Indian is 60kg giving us a total EV mass of (320 + 180)kg = 500kg.

Thus, the total kinetic energy of the vehicle is $(0.5)(500)(v^2)$ = $250v^2$.

2.3.2 Energy Lost due to Air Resistance – Drag

The equation for calculating Force exerted by wind resistance (F_w) is as follows –

$$F_w = \frac{1}{2}C_d A \rho v^2$$

Where C_d = Coefficient of Drag, A = windward area, ρ = air density and v = velocity of the vehicle.

$$\rho = \frac{Pressure}{(Gas\ constant)(Temperature)}$$

Air pressure in Delhi = 101300 pascals, gas constant = 287.058 and average temperature = 308K.

$$\rho = \frac{101300}{(287.058)(308)}$$

$$\rho = 1.146\ kg/m^3$$

We can assume windward area to be (length x breadth) of the front face = (0.96m)x(0.74m) = 0.7104m^2. Also, the calculated coefficient of drag of an E-Rickshaw is 0.5[1].

Thus, F_w can be calculated as follows:

$$F_w = \frac{(0.5)(0.7104)(1.146)v^2}{2}$$

$$F_w = 0.2035v^2$$

2.3.3 Energy Lost due to Rolling Resistance

Rolling resistance (F_r) can be calculated using the formula –

$$F_r = fmg\cos\alpha$$

Where f = coefficient of rolling resistance, m = mass of the EV, g = gravitational acceleration and α = angle of inclination. However due to our first simplifying assumption, we know that the angle of inclination (α) = 0. Therefore, $\cos\alpha$ = 1 and $F_r = fmg$.

Figure 5: Coefficient of rolling resistance in relation to tire pressure and EV speed

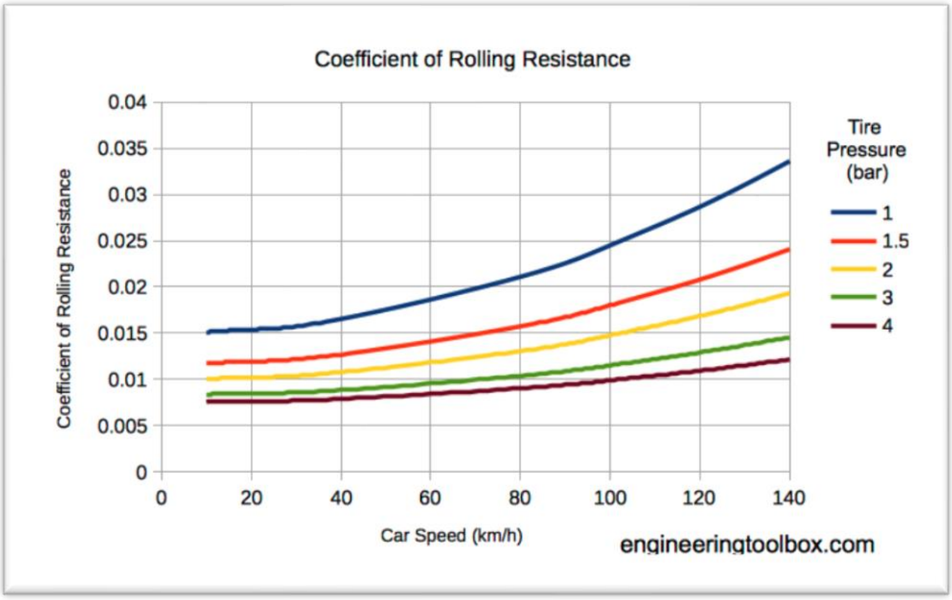


Diagram Reference [3]

From the above table we can see that coefficient of rolling resistance of an E-Rickshaw wheel at 2 bar tyre pressure[2] is 0.01. We can also see that the coefficient of rolling resistance remains constant till 28 km/h, the maximum speed of the E-Rickshaw.

Therefore,

F_r = (0.01)(500)(9.8) = 49N

2.3.4 Total remaining energy that can be captured

2.3.2 Force exerted by drag = $0.2035v^2$

Therefore, Energy lost due to drag = $\int_0^T 0.2035v(t)dt$

= $(0.0678)v^2t$

Where T = total braking time, t = instantaneous time and $v(t)$ is the velocity function.

2.3.3 Force exerted due to rolling resistance = 49N

Therefore, Energy lost due to rolling resistance = (49N)($\frac{vt}{2}$)

= (24.5)υt

Thus, Energy available at the shaft of the motor = $K_i - E_d - E_r$ where K_i = Initial Kinetic Energy, E_d = Energy lost to drag and E_r = Energy lost to rolling resistance.

Energy available = E = $250v^2$ - $(0.0678)v^2t$ - (24.5)υt

Table 1: From my tests, we recorded the initial speed and stopping time of the EV. Using these values of v and t and the mathematical model I created, I plotted the table below.

Test No.	Initial Velocity (Km/h)	Initial Velocity (m/s)	Time to Stop (s)	Energy Generated (J)
1	5	1.389	4.2	338.756
2	10	2.778	5.3	1565.825
3	15	4.167	6.1	3711.033
4	20	5.556	7.4	6694.494

From this table we can see the amount of energy that can be harvested from the shaft of the motor during a regenerative braking operation at 4 different speeds. The rated speed of E-Rickshaws ranges from 25-28Km/h but in 1+2 capacity orientation reach a maximum speed of 20Km/h.

2.4 Estimation of Braking Cycles in a Day of E-Rickshaw Operation

This section of the paper deals with an estimation of how many times a 'braking operation' takes place in the average E-Rickshaw ride.

Calculating the braking operations is made easier by taking the case of an E-Rickshaw acting as a shuttle. I took an E-Rickshaw between two points 1.7km apart 3 times. I counted the number of braking operations that took place and created the table below.

Table 2: No. of braking operations between Sector-30 and HUDA City Centre (1.7km apart)

Δv (Km/h)	Ride 1	Ride 2	Ride 3	Average
5	5	4	5	4.67
10	6	5	6	5.67
15	7	8	8	7.67
20	4	5	4	4.33

Note: Δv specifies the change in velocity during the braking operation as all braking operations do not end with 0 velocity. Due to simplifying assumption (ii), as the deceleration is constant, our equation is not affected by different final and initial velocities – only their difference.

The average number of 1.7km shuttle rides the EV can do in a single day is 52. Therefore, average number of braking operations can be found.

Table 3: Total energy generated by each braking operation

Δv (Km/h)	Average braking operations	Energy per operation (Table 1)	Total Braking operations	Total Energy (J)
5	4.67	338.756	242.84	82,263.507
10	5.67	1565.825	294.84	461,667.843
15	7.67	3711.033	398.84	1,480,095.24
20	4.33	6694.494	225.33	1,709,305.153
			Total:	3,733,331.743

3. POTENTIAL INCREASE IN RANGE

The E-Rickshaw has 4 inverter batteries on it with a capacity of 100Ah each. Thus, the total energy storage onboard an E-Rickshaw is 400Ah at 12v = 4800AhV (4800Wh)

1Wh = 3600J
Thus, 4800Wh = 17,280,000J

Our regenerative system can capture ≈ 3,733,331J of energy

This is 21% of the stored energy onboard the E-Rickshaw. Ignoring the inefficiencies of the charging circuit and motor controller, this means that the range of an E-Rickshaw can pe increased but up to 21km.

For an E-Rickshaw driver, 21km is 12 shuttle rides. At 4 passengers at Rs. 10 (0.14$) that is equal to a greater earning of Rs. 480 (6.8$). For a driver who earns Rs. 1000 ($14.28) in a day, that is an earning increase of nearly 48%.

4. NEXT STEPS IN MY RESEARCH

All the papers I reference in this paper have no mention of next steps. I feel that the next steps in any research will show the way forward for that technology – from paper to a prototype.

This paper only discusses an analysis of the energy that could be restored from an EV such as an E-Rickshaw. The next steps in my research are to analyse the inefficiencies of using a BLDCM as a generator and to design a charger that can efficiently charge Lead-Acid batteries with a 3-phase AC supply.

Though this technology can seem to be highly beneficial on paper, it would be worthless if it is too expensive to implement. The prototype that I am currently working on is designed to be entirely modular, allowing it to be installed to a pre-existing, off the shelf E-Rickshaw.

5. CONCLUSION

I decided to take an interesting angle in this paper to see what the energy production would be like if regenerative braking was not paired with a mechanical brake. In our tests, as the current drawn by our load increased, the rate of decrease of EV velocity increased, slowing the EV down faster. Thus, a balance must be struck – if too much current is drawn too quickly, damage to the armature may occur while if current is not drawn fast enough, a mechanical brake will have to be incorporated.

The increase in efficiency calculated in this paper is 21%. For an EV in a shuttle system, the range is not of concern to the "Hub" or Rental company but is a great concern to the driver. The drive pays Rs. 500 (7.14$) to rent the E-Rickshaw for one full charge. This means that the greater the range of the EV per charge, the greater profit he will make. On average, an E-Rickshaw driver makes a gross revenue of Rs. 1500 (21.42$) out of which Rs. 1000 ($14.28) is his profit. An increase in range of 21% equates to an approximate increase in profit of 48%, a huge impact on his day's earnings.

The results show that regenerative braking is a viable means of increasing fuel efficiency and the livelihoods of those behind the wheel. Regenerative braking is also a concept that can be introduced directly into the 3-phase drivers to reduce assembly time and complexity of the system.

6. REFERENCES

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