Comprehensive Analysis of Regenerative Braking System in E-Mobility Applications

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Abstract -- **We're sluggishly approaching the electric vehicles era. The widespread use of electric vehicles has a number of problems, such as lengthy battery charge times and insufficient charging stations. For this reason, we present a regenerative braking system that permits a vehicle to induce energy each time brakes are applied. In Regenerative retardation system most of the energy is transformed into electrical energy and this energy is able to be kept for later usage. Driving a machine involves numerous retardation events leading advanced energy losses and lesser implicit savings. The main purpose of this design is to capture that lost kinetic energy during retardation, and store it in a storage unit. We have the ability to partially balance the kinetic energy of motor vehicles thanks to the employment of regenerative retardation systems in motor vehicles. It advances us one step closer to a transportation system devoid of pollutants.**

Keywords: Electric Vehicles, Regenerative braking,

I. INTRODUCTION

AS far as we are aware, using only limited petroleum resources will prevent the dream of the popularization of cars from being realized. Therefore, the development of regenerative braking systems in electrical vehicle is a key strategy for problem solving [1]. Kinetic energy is transferred to heat as a result of rubbing of brake pads against wheels when a typical vehicle applies its brakes. The energy is effectively squandered because this heat is transported by airstream. Depending on how frequently, forcefully, and for how long the brakes are used, a whole amount of energy is wasted in this manner.

Regenerative braking is a technique in which a storage mechanism temporarily holds some of the vehicle's kinetic energy. During deceleration, an energy reserve is commonly wasted in the brakes, thus a power transfer system directs that energy there. In this method, a significant amount of the vehicle's energy is conserved to be used either for later vehicle acceleration or for other electrical purposes [3].

Driving a car includes a lot of braking, which results in increased energy loss that could be used and bigger potential savings. Even more opportunity for economy exists with the usage of buses, taxis, delivery vans, and other vehicles. For a given energy input regenerative braking increases a vehicle energy output. [4].

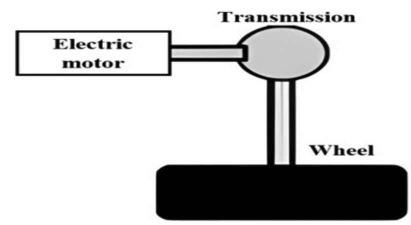

Figure 1. Motion transmission.

II. THE MOTOR AS A GENERATOR

Utilizing an electric motor that also generates power, the most popular form of regenerative brake. The electric car employs its electric motor as an electric generator when employing its regenerative braking system [5], when braking operating as a generator and feeding its output to an electrical load, which produces the braking effect. To partially regain the energy lost during braking, hybrid gas/electric vehicles use regenerative braking. When the car is operating in electric mode, this energy is stored in a storage battery and it is used to operate the motor later. [6].

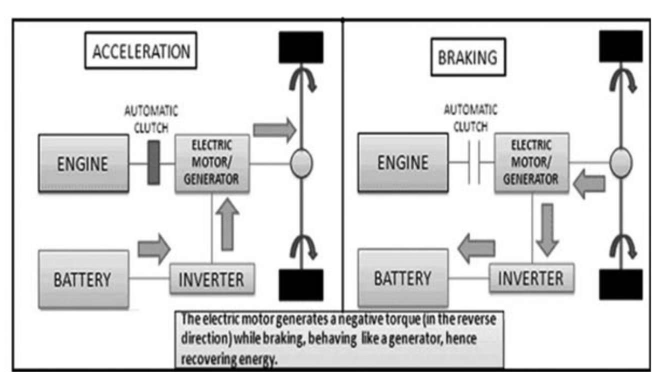

Figure 2. Block diagram of regenerative braking system.

The following characteristics should be adhered to in order to create a good regenerative braking system [7]:

- To effectively preserve energy.
- A high-capacity energy reserve that has a low mass and volume density.
- A high-power rating that enables rapid flow of big amounts of energy.
- Not necessitate overly intricate control mechanisms to connect it to the vehicle transmission.
- Through this mechanism smooth power is delivered.

III. BASIC ELEMENTS OF REGENERATIVE BRAKING SYSTEM

For the regenerative braking system to function, four components are necessary [8].

A. Energy Storage Unit (ESU)

The power in the form of electrical energy is stored in the batteries of electric vehicles. The range of the vehicle is determined by the quantity of energy it can store. The state of charge of batteries (SOC) is the volume of charge that the storage device has stored. Electric car batteries are identified by their fairly good power to weight ratio and energy density and weight to energy ratio.

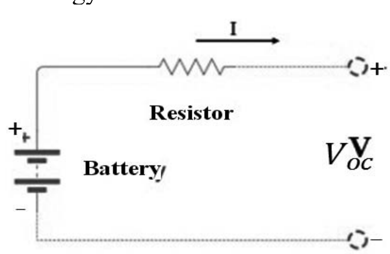

Figure 3. Simplified battery module.

The graph compares several batteries based on parameters for both volumetric and specific energy densities. The Lithium-ion battery offers the highest specific energy density and is smaller and lighter in weight.

Due to their affordability and dependability, lead acid batteries are most frequently utilized. The battery's performance will be negatively impacted if it is charged above its SOC. However, lead acid batteries can withstand voltages higher than their rated range without experiencing performance loss.

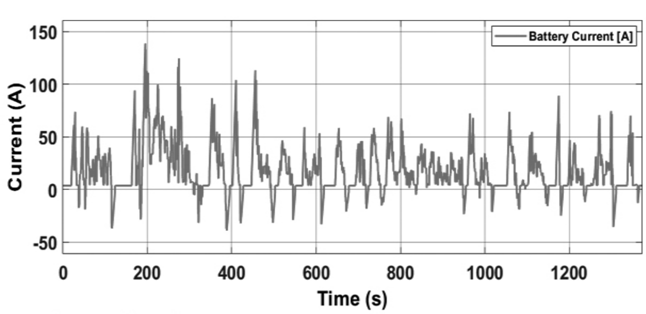

Figure 4. Battery voltage variation (UDDS cycle).

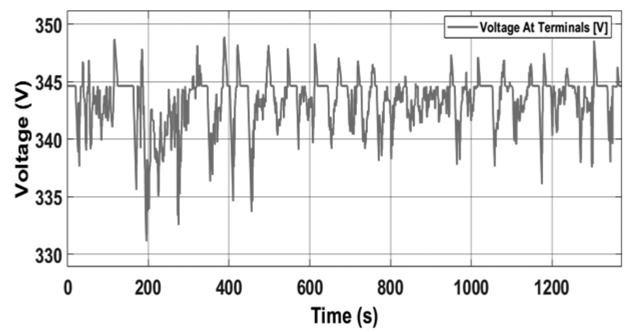

Figure 5. Battery current variation (UDDS cycle).

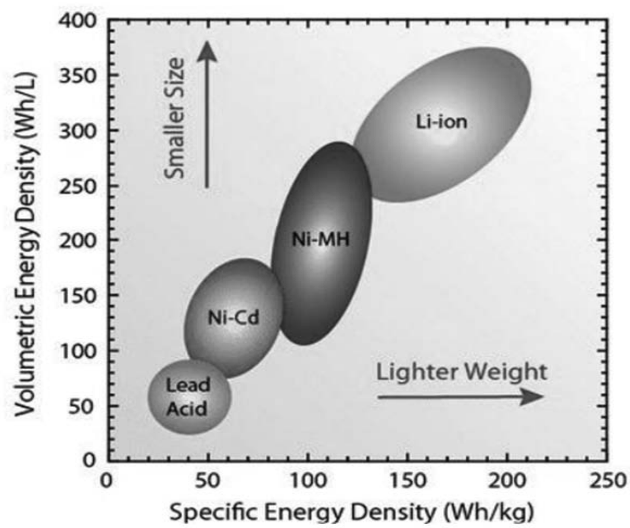

Figure 6. Comparison of different batteries.

- To absorb extra engine energy during light load operation;
- To collect and store brake energy

These are some preferences considered for productive storage of energy:

- Energy transfer rates is higher
- Specific energy storage density is higher
- Minimal area requirements

Regenerative braking can recover energy that can be kept in one of three things:

- A flywheel,
- An Electrochemical battery
- Compressed air.

B. Continuously Variable Transmission (CVT)

The energy storage unit needs a transmission that can easily regulate energy flow from the wheels of vehicle in order to meet speed demands and steeple-type torque.

C. Controller

Engine control is in the "ON-OFF" position. Accordingly, the engine runs "ON" until the energy storage unit reaches the specified charge capacity, at which point it is disconnected and stopped until the energy storage unit charge hits the minimum level necessary.

D. Regenerative Brake Controllers

Electrical devices known as brake controllers are capable of remotely controlling when to start and stop, as well as how much pressure to apply to the brakes. During braking, the electricity produced by the motor is distributed by the brake controller to the capacitors or batteries. It makes sure that the batteries get the appropriate amount of power while also making sure that there is not too much electricity coming in.

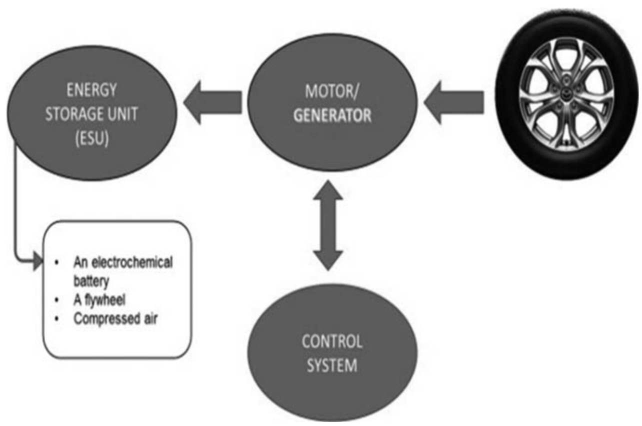

Figure 7. Regenerative braking system braking mode.

IV. CONTROL STRATEGIES IN SYSTEM

The purpose of the brake controller is to calculate the rotational force, torque, and produce electricity to supply back to the battery while continuously monitoring the wheel speed. The enhanced motor control algorithm offers total control over motor torque in both driving and regeneration situations.

Fuzzy logic control: The current system is now more effective because of artificial intelligence. The influence of many parameters on the distribution of braking force in electric vehicles is an excellent way to illustrate the fuzzy logic control technique. Therefore, the EV brake force distribution is applied using fuzzy control theory. A membership function (MF) is used to define input variables. The mapping from each point in the input space to a membership value between 0 and 1 is defined by a curve. The needed braking power, SOC, and vehicle speed are the preferred fuzzy controller inputs. Results are the machine receiving energy from regenerative braking.

Flywheel Implementation: The term "electromechanical battery" refers to a flywheel. It is a storage mechanism for inertia energy. When more energy is given than is needed, a flywheel stores it and releases it when Demand for energy is greater than supply.

Utilization of flywheels is due to:

- Design and operation flexibility
- A 90% increase in cycle efficiency
- Even though it has little impact on the rapid charging profile cycle of life
- More than ten years of extensive upkeep

Use of Ultra-capacitor: A high-capacity capacitor with substantially greater capacitance values than regular capacitors is known as an ultracapacitor. Its characteristics are in between those of rechargeable electrolytic capacitor batteries. The addition of an ultracapacitor to an electric vehicle increases storage capacity, which in turn boosts the vehicle's range.

Advantages of using Ultracapacitor are;

- Improves EV's transient performance
- Compared to electrolytic capacitors it stores 20% more energy
- During acceleration and braking it avoids fast and sudden battery discharge

The four essential parts of this system are an aluminium smoothing inductor Ls, a DCDC converter using an IGBT switch, an ultracapacitor bank, and a battery pack. By activating the Switch T1, energy will be transferred from the ultracapacitor bank to the battery during the charging process. Switch T2 is activated when the battery is being discharged, giving power to the bank of ultracapacitors. Between the battery and the converter, the ultracapacitor serves as an intermediary stage, hence enhancing energy storage.

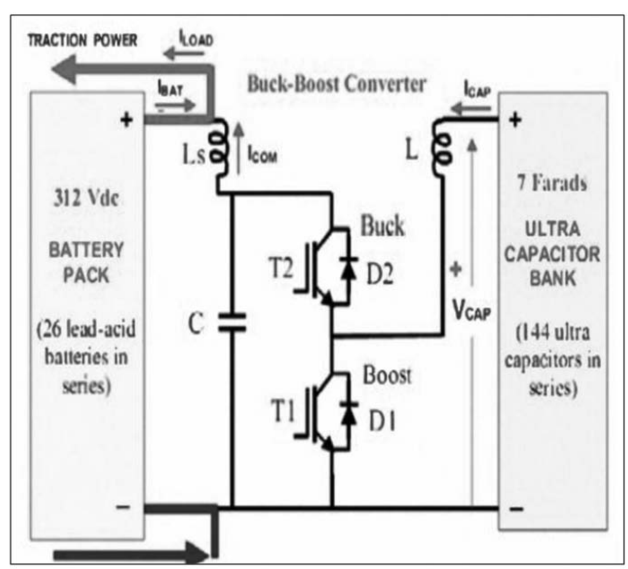

Figure 8. Buck-boost converter with ultra-capacitor bank across DC link.

IV. VEHICLE LAYOUT WITH REGENERATIVE BRAKING SYSTEM

Figure 3 depicts the suggested layout. In the event of an electric automobile with non-regenerative brakes, the gearing unit (G) divide the shaft connecting the differential to the motor. The motor (M) and D.C. generator (G) are connected to the gearing unit's two diminutive gears at their respective ends via clutches C1 and C2. Clutch C1 is functioning normally under normal driving conditions. By sending it via gearing unit, this transmits driving torque to vehicle axle. When the driver applies the brake, the clutch C1 releases, and C2 begins to engage. The torque from the wheels is then delivered to the generator (G) in the opposite direction. Due to this, the generator (G) converts mechanical energy into electrical energy, which is then transmitted by a voltage regulator to the battery pack.

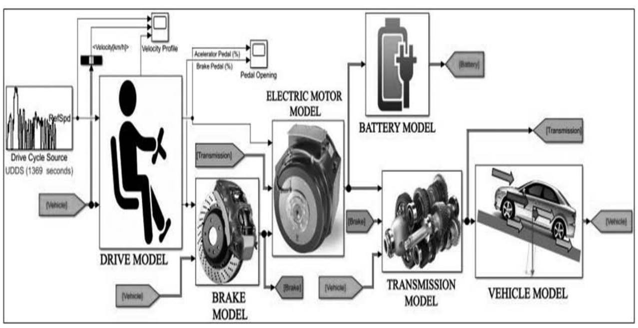

Figure 9. Layout of proposed regenerative system.

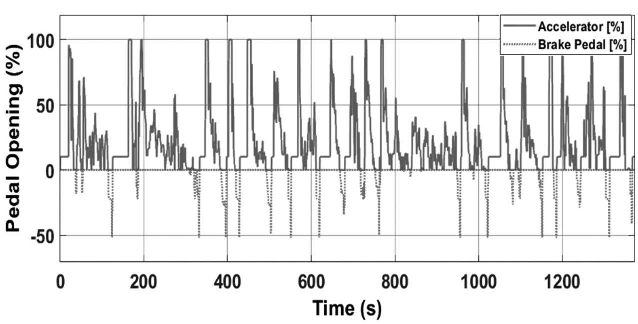

Figure 10. Pedal actuation (UDDS cycle).

V. THERMODYNAMICS EQUATIONS

The motor/generator and the battery work together in a two-step process known as regenerative braking. The generator turns the original kinetic energy into electrical energy, which the battery subsequently transforms into chemical energy. The flywheel is more effective than this method. The generator's effectiveness can be represented as [11-12]:

$$\eta_{gen} = \frac{w_{out}}{w_{in}}$$

where

- W_{in} refers to the work puts into the generator
- W_{out} refers to the work that the generator produces

The generator's sole work input is the car's initial kinetic energy, and its sole work output is electrical energy. This equation can be rearranged to account for the power generated by the generator.

$$P\text{gen} = \eta\text{gen}\ \eta\text{batt}^{2}\ /2\Delta t$$

where

- Δt refers to how long the car brakes
- m is car's mass.
- v represents just before braking car's starting velocity.

The battery's effectiveness can be summed up as follows

$$\eta_{batt} = \frac{P_{out}}{P_{in}}$$

where

- $Pin = Pgen$
- $Pout = W\text{out}\ \Delta t$

The quantity of energy generated by the regenerative braking is represented by the battery's work out. This is represented by:

$$W_{out} = \eta\text{batt}\ \eta\text{gen}\ mv^2/2$$

VI. EFFICIENCY OF REGENERATIVE BRAKING

When compared to a vehicle with an internal combustion engine, an electric vehicle's powertrain is distinguished by greater efficiency. Regenerative braking, however, can only recover a portion of the energy due to conversion losses. Many researchers have been looking at the process from a "braking" point of view, just studying the distribution of braking torque during regeneration and paying no regard to potential energy gains. Serial and parallel regenerative braking is the phrase for the combined operation of both mechanical and regenerative braking [3]. Efficiency of regenerative braking can be expressed as increase in EV's range. Studies [3, 10] have shown that generally driving range increase varies between 8 to 25%. Similar results can be found in following studies – driving range increase of 15% and more in metropolitan areas with many opportunities of braking [11], while [15] have estimated an increase in range roughly by 16%. Another way to express regenerative braking's efficiency can be as a ratio of energies. A case study of regenerative braking efficiency [19] of electric public transport vehicles studies the efficiency as a ratio of converted useful brake energy Wreg to entirety of brake energy Wbrake defined as vehicle regeneration efficiency (VRE), *i.e.*

$$VRE = W_{reg}/W_{brake}$$

Additionally, they have established a system regeneration factor (SRF) as the proportion of regenerated energy to source-generated propulsion energy. Their system regeneration factor was estimated to be between 22 and 23 percent.

An energy recovery rate ηr presented by a ratio of recovered energy Erb to energy that is consumed during whole driving cycle (driving Ek and braking Eb energies) as

They have also presented comparative research of regeneration with parallel braking, serial braking and single pedal driving strategy. Obtained results have shown that recovery rate ηr of parallel braking is between 8 and 11%, series braking between 15 and 19%, while results of single- pedal driving are even further than 26% [21].

VII. LIMITATIONS OF REGENERATIVE BRAKES

The system has a number of potential drawbacks in addition to the natural decline in regenerative braking effectiveness at low speeds. Among the most notable are [4, 7, 13]:

- On “drive wheels,” regenerative braking is only effective.
- In most cases, regenerative brakes don’t offer enough stopping power during emergency stops.
- A regenerative system’s efficiency is constrained by things like the electric motor’s output and the energy storage system’s storage capacity.
- Some regeneration systems are compelled to employ extra “dynamic braking” that doesn’t retain the recovered kinetic energy.
- The use of conventional regenerative systems with non-electric, non-hybrid cars is not possible.

VIII. ADVANTAGES OF REGENERATIVE BRAKING SYSTEM

There are some advantages of regenerative braking system in electrical vehicles [2,7,14,15]:

- An improvement in a vehicle’s total energy efficiency.
- Increased Fuel Economy – Reliant on power train design, duty cycle, component efficiency and control scheme.
- Decreased Cost of Replacement Brake Linings.
- Decreased Brake Wear.
- Energy efficient due to fewer transformation losses than in storage applications.
- Less use of conventional mechanical brakes results in progressively less wear.
- Reduces pollutants associated with energy generating

IX. CONCLUSION

With an expansive and expanding rail conveyance network, energy effectiveness will always be an important element of environmental impact and operation costs. The automobiles' regenerative braking system accomplishes the goal of preserving some of the energy that is departed throughout braking. Additionally, it may be more efficient and used at high temperatures than a traditional braking system. Based on the findings of several tests, the system can recover the energy up to 30% of total given. The compass of the regenerative braking system is broad for future development and energy savings. New drive train designs that are created with regenerative braking in mind, new motor types that are better as creators and electric systems that are prone to fewer energy losses are all upcoming advancements in regenerative brakes [19].

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