

OPERATION OF REGENERATIVE BRAKING IN ELECTRICAL VEHICLES AND COMPARISON WITH CONVENTIONAL BRAKING

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ABSTRACT

Braking is the primary and fundamental feature of a vehicle. It can be regarded as one of the important and primary things, and so it's important to have efficient braking system. The mechanical braking system which is the most used braking system is sometimes inefficient and its one of the limitations is that the kinetic energy of the vehicle that is produced after braking is wasted as heat and thus this phenomenon leads to reducing the efficiency by majorly affecting the fuel and the optimization of fuel.

In, the city areas and the areas having dense population it's necessary to apply brake every time and thus decreasing the efficiency of motor. This makes the energy loss wider and thus we need effective braking system. So, engineers have invented "REGENERATIVE BRAKING SYSTEM" to regain the kinetic energy that is lost as heat during the old braking method. But, by the law of physics though we can't recoup the whole energy but notable amount can be recovered and can be stored in the battery or super-capacitor.

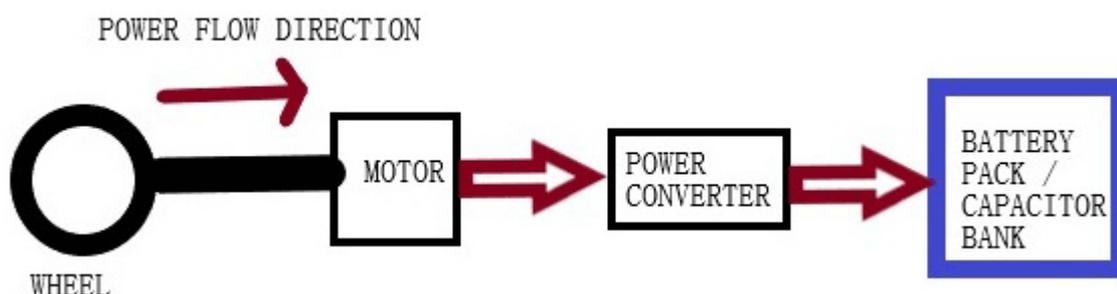
Keywords: Regenerative braking, electric vehicles, kinetic energy, working.

1.) OBJECTIVES AND METHODOLOGY

1.1) INTRODUCTION

The notion of the regenerative braking which is enacted in day-to-day vehicles is used with the help of fly-wheels. So, basically fly-wheels are the disks that are with high inertia and it rotates at a high speed. Thus, we can say that it behaves as a device or container which can store the dissipated kinetic energy of the vehicle during the process or time of braking. The, residual energy which is stored can be used for assisting the vehicle during load or the slopes having the up-hill moment.

Fig1) Algorithm of Power flow direction during regenerative mode.



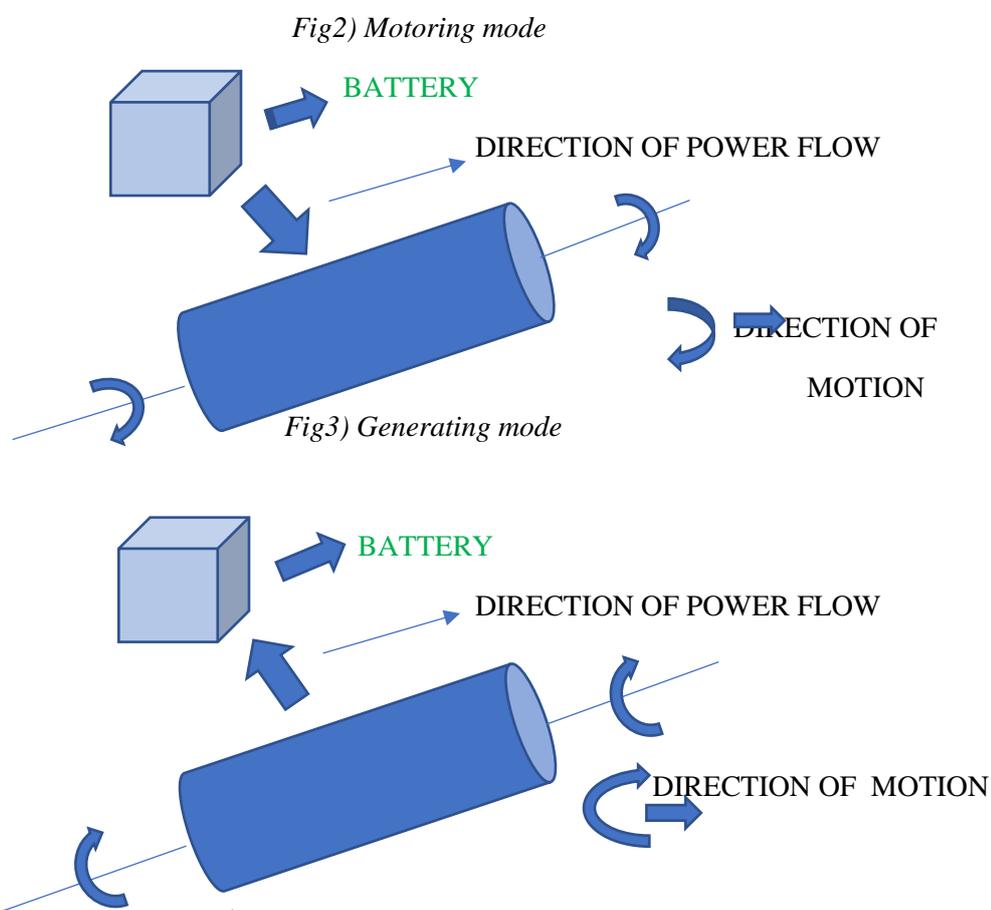
Source:- www.workingofregenerativebraking.com

The regenerative braking is the mechanism which does not get triggered on plain road surface or the area which is covered by smooth surface. It is only seen on those type of roads where we have to apply brake on speed breaker or the rough surface area which contains the irregular area and some pits. This type of braking is observed when the level of battery is charged up to full extent because braking needs to be effect by energy.

In EV's (electrical vehicles) we can assimilate this braking system in more effective way with the use of electronics and thus reducing the need of heavy fly-wheels, nor it will add to the extra weight of vehicle. At the process of breaking the amount of kinetic energy that is lost can be re-converted to electrical energy and can be stored in battery or ultra -capacitor. Thus, by saving the energy we can control the energy loss and can use it whenever we want by again converting to mechanical energy at the time of load gaining or load taking by the car or any other vehicle.

1.2) FUNCTIONAL PRINCIPLE OF REGENERATIVE BRAKING

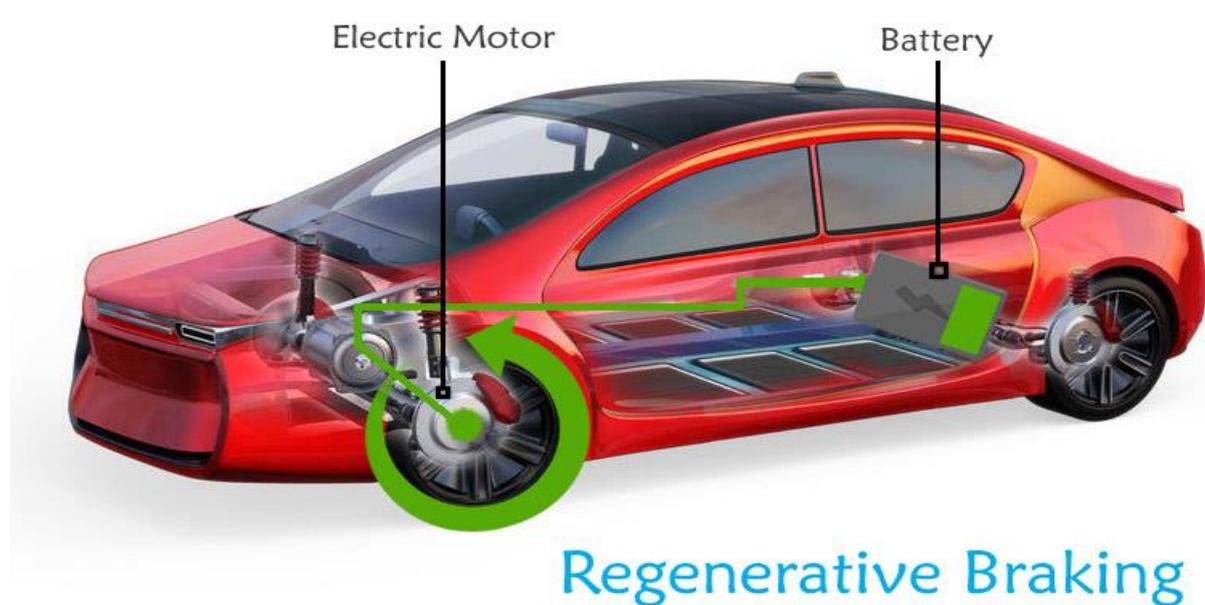
Regenerative braking method uses the mechanical energy which it gets from the motor and converts electrical energy and it flows back to the battery. There are instances when we need to stop the car or slow down the car and when we apply the force to apply brakes, the motor present there starts working in the reverse direction and thus leading to stop the car ultimately. For an instance it is very primary thing to know that when motor runs in the opposite direction of validate it acts and works as generator.



In Fig2) the normal running condition of motor is been shown where the motor runs in forward direction and that receives energy from battery. For an instance when we employ this type of braking system in electrical vehicles it saves the fuel, fuel economy is stabilized, emission is lowered and the energy loss is saved up to a great extent and thus we can clearly mention that this braking can eradicate traffic, also it can be seen that the energy loss is very low, almost equivalent to negligible.

In Fig3) the opposite condition of motor can be seen where the motor is running in the reverse direction and can be seen in the “generator mode”. Thus the generating mode of the motor comes into picture and it gives energy back to the battery. In this type of mode and when the car or vehicle is to be started and it has to take off the load this energy can be used efficiently so fuel economy is increased.

Fig4) Proto-type of a car which has employed regenerative braking system.



Source: - www.workingofregenerativebraking.com

The working of mechanical braking system is that, whenever we apply brakes a reverse torque is generated in the wheel (motor) and the vehicles come to halt. Likewise, in regenerative mode of braking negative torque is initiated in the motor of wheels with the help of motor controller. At this time of running, the controller of the motor is functioned to recoup the whole kinetic energy such that it can store the regained energy in battery or the capacitor banks. Apart from saving the fuel and saving energy, regenerative braking also enhances the range by 8-15% and also, it's the most effective way of braking.

1.3) LITERATURE SURVEY

Regenerative braking system is one of the most famous and most popularly used as this method improvises the most typical problem and that is the energy conservation problem. We can save up to 25% energy and thus can give our hand to the eco-friendly system of cars. Many modules, papers and books have been published in accordance with the regenerative braking system. Various methods and terms are used in this paper and those are derived from the researcher's knowledge.

This braking system has achieved and continued to have a good impression on automotive industry and so there are many chances that there can be very much bright future in this field. Also, there are some conditions in which this system can't be used. For e.g., high temperature of battery we cannot use that system as it tends to increase the overall temperature of the system.

Thus, it's very important to have proper blending of the torques that have been produced due to the hydraulic braking system and the regenerative braking system. If these torques are not in line then there would be a difference in braking and can make the vehicle disturbed due to the improper alignment of the braking systems.

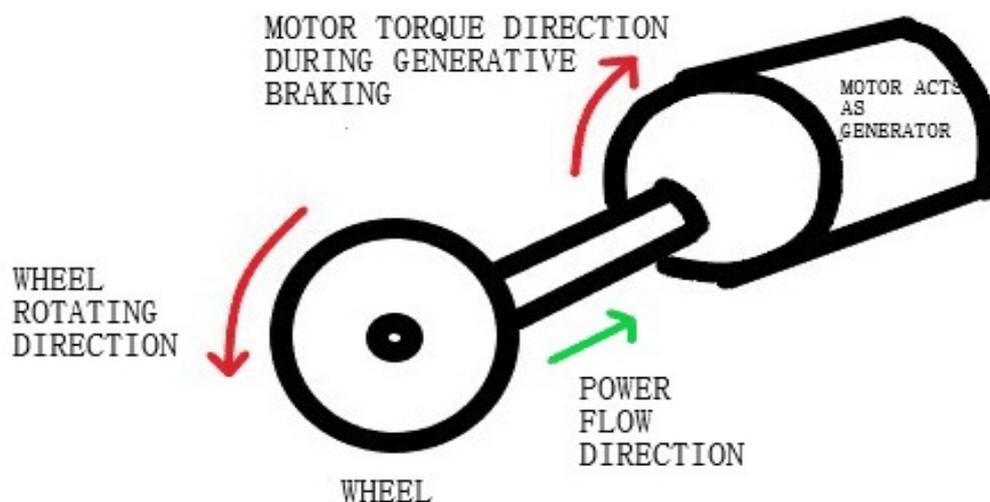
2) RESEARCH METHODOLOGY

2.1) OPERATION OF REGENERATIVE BRAKING ELECTRIC VEHICLE

For an instance let's assume the car is been imbued with a three phase induction motor for the purpose of propulsion. It is clear with the help of speed-motor characteristics that while induction motor runs at a speed more than synchronous speed then the slip(s) becomes negative and thus the motor works as an induction generator (alternator). The synchronous speed can be defined as the speed of rotating magnetic field of the stator which is produced due to the injection of three phase supply.

At the time of starting of motor, the EMF which is induced in the motor is at the peak level. Now when the motor starts to rotate fast the induced EMF decreases because it's a function of slip and inversely proportional and thus when the motor reaches to the synchronous speed the induced EMF becomes zero and thus vanishes in motor. Now if the rotor is rotated at the speed above than this, EMF will be induced and, in the prevailing situation, it happens oppositely that the motor gives the active power back to the source. When the brakes are applied to halt or decrease the speed of the vehicle then it is not advisable to run the motor above synchronous speed at that time so here the motor controller comes in picture.

Fig5) Torque and power flow direction when motor works as a generator.



Source: - www.workingofregenerativebraking.com

Now, by assuming one situation it should be clear that how this braking works in the electrical vehicle. For an example let's take that motor is rotating at the rpm of 5000 also the fundamental frequency that is supplied be 150 Hz and at the time of braking we need to bring down or reduce the rpm to lower levels or zero. The controller coming into the picture depends upon the input that we get from the brakes and the pedal sensor and starts to carry out its functioning. When this process starts the controller automatically sets the fundamental frequency inferior than 150 Hz and will make it equal to 80 Hz and thus making the synchronous speed 2200 rpm. When we see from the reference of motor controller the speed of motor is more than its synchronous speed and as now, we are intended to reduce the speed while braking, the motor will act as a generator until 2200 rpm and in this time span, we can take out or extract power from the motor and store it in the battery or the capacitor bank.

It is here noteworthy point that the battery continues to supply the power to the three phase induction motors during the process of regenerative braking and this is because the magnetic flux of induction motor is zero when the power given(source) is 0(OFF). Also, it is known that motor enacting as generator draws the power which is reactive to produce the linkages of flux and gives active power back. The law is different for every different motor to recover or regain the kinetic energy. For instance,

- 1) Permanent magnet motors can act as a generator even in the absence of source power because permanent magnets are present in the rotor to generate magnetic flux.
- 2) Other similar types like DC shunt motor and others have residual magnetism in it which waives the need of external excitation required to produce or generate flux which is magnetic in nature.

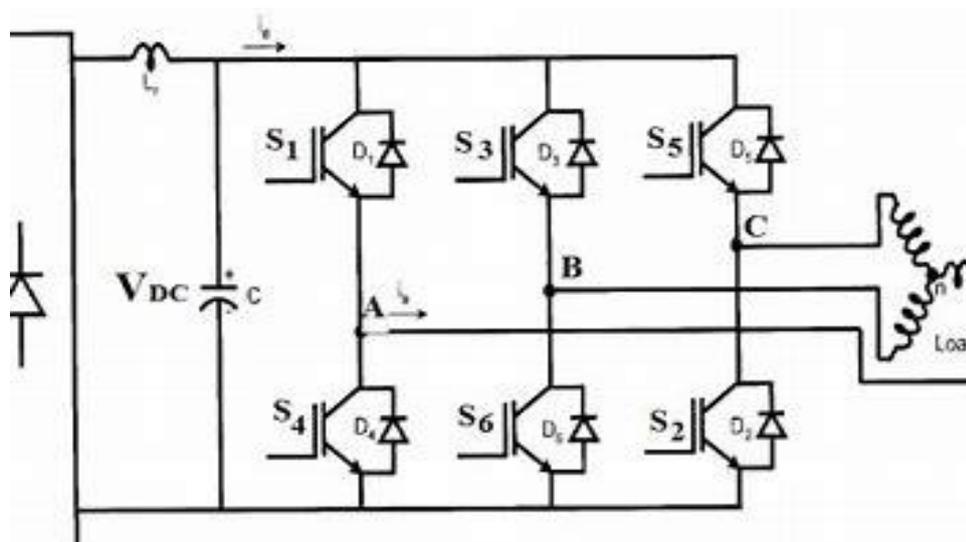
In majority of vehicles that are running on the electrical principal, the motor is joined to the singular drive axle (mostly to the rear-wheel drive axle) and thus its necessary to use a mechanical braking or the hydraulic braking for the front wheels. And this arises the necessity that the controller should maintain coordination between both mechanical braking and the electronic braking system when we apply brakes.

3) ANALYSIS AND OBSERVATION

3.1) OPERATION OF MOTOR IN ELECTRIC VEHICLES

The figure down here shows the three-phase and no brush connected DC motor, the motor here is controlled by an inverter which is given power from supply battery. The load is connected to the end of the 3- phase bridge inverter. D1-D6 are the free-wheeling diodes and the S1-S6 are the switching devices. This inverter gives efficient way to control motor by their switching devices and thus deducting some of energy.

Fig6) Equivalent circuit of inverter driven 3phase brushless motor.



Source: - www.3-phase-bridge-inverter-images.com

The working of this inverter driven motor is a complete commutation cycle of 360° electrical consists of 6 equal intervals. The switches are controlled in phase sequence used with control circuit based on rotor position sensors. For the effective control of torque developed by motor controlled by the inverter circuit. The operation table is for the gating scheme is given here.

Table 1: - Operation table for the gating scheme

Sr. No	Interval	Device conducting	Incoming device	Outgoing device
1	I	5,6,1	1	4
2	II	6,1,2	2	5
3	III	1,2,3	3	6
4	IV	2,3,4	4	1
5	V	3,4,5	5	2
6	VI	4,5,6	6	3

Source: - MD Singh, KB Khanchandani, Mc-Graw Hill, second edition

3.2) BALANCING OF ENERGY

We can clearly see that kinetic energy is been converted and so the fundamental problem that is need to be solved is that how much of the energy is been recovered successfully. Approximation of the recouped energy is very important to count as for design process it holds very important calculation.

- Regenerative ratio

$$\mu = \sum (V_{br} / V_{kin})$$

where,

$$V_{kin} = \sum 0.5m(V_2^2 - V_1^2)$$

$$V_{br} = \int_{t=0}^{t=end} (E_k - I(t)R(t)) I(t) dt$$

E_k is the battery voltage, $I(t)$ is the battery current, $R(t)$ is the charging resistance, V_1 is the initial velocity, V_2 is the final velocity.

3.3) SUBSYSTEM FOR DRIVER

When an upward slope comes in the way the driver needs to accelerate and this acceleration produces a corresponding driver torque. The process of production of regeneration is started only after brake pedal is pressed.

The mechanical energy that is absorbed by the vehicle when driving on a specific pattern and thus it primarily depends on the three main effects:

- 1) aerodynamic friction loss
- 2) rolling friction loss
- 3) energy dissipated in the brakes

$$M_v \frac{dv(t)}{dt} = F_t(t) - (F_a(t) + F_r(t) + F_g(t))$$

This equation shows the longitudinal dynamics of the road vehicle.

4) THE SIGNIFICANCE OF CAPACITOR BANK OR ULTRA CAPACITORS

During the action of braking there's a sudden jerk and the speed reduces very quickly; we need to stop or reduce speed immediately. Therefore, the braking system is of very short duration, batteries have limitations and shortcomings so we cannot inject a huge amount of energy in the battery because it can cause damage to battery or severe problems can be occurred at the time of braking and it can be a risk and so to avoid this type of disadvantage, we need a capacitor bank or ultra-capacitors to the regenerative braking system. This capacitor can discharge or charge for many cycles without any harm or inefficient way, thus making capacitor bank is a prominent part of the system.

Ultra-capacitor is a device which responds quite fast as compare to other capacitors to help in capturing the energy surges effectively due to regenerative braking operation and the primary reason to choose this type of capacitors are that these are very efficient and are able to store 20 times much greater energy than that of a normal electrolytic capacitor. This kind of system gives a rise to DC-DC converter. At the time of acceleration, the "boost operation" helps the capacitor to discharge up to a finite extent maximum value. During breaking the "buck operation" helps and makes the capacitor charge up to maximum value having a good transient response and this is one of the important characteristics of the ultra-capacitor. Thus, this helps to store the energy apart from battery and giving rise to high efficiency of the vehicles and extending their range to a great extent and it can also assist to acceleration surge so that no damage is been done by the vehicle.

Fig 5) Ultra capacitor in use



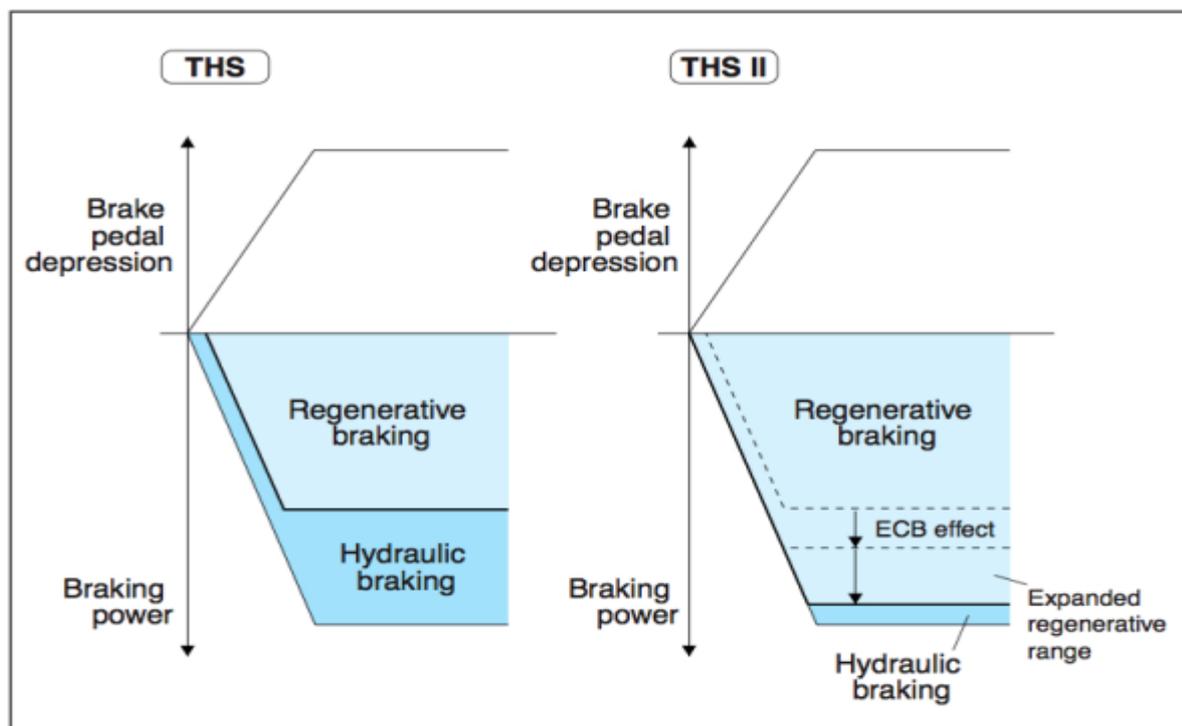
Source: - [www .ultra-capacitor images.com](http://www.ultra-capacitor-images.com)

5) PROS OF REGENERATIVE BRAKING OVER CONVENTIONAL BRAKING

5.1) ENERGY PRESERVATION:

The function of flywheel is to imbibe when braking is done with the help of a clutch system slowing down the car and making the car halt at the needed position. Now to accelerate another clutch system is advocated which connects the flywheel to the drive, thus leading to the higher speed to car and accelerating it. Energy is thus, conserved and is not wasted in the form of heat or some other dissipations which normally happens in the mechanical braking system.

Fig 6) Recent Hybrid braking complaints



Source: - [www. Images comparison of regenerative and conventional braking .com](http://www.Images.comparison.of.regenerative.and.conventional.braking.com)

Fig THS depicts the braking power of both the braking systems and the comparison of both braking systems and this graph clearly shows that the portion of regenerative braking is less than the hydraulic which sets a benchmark as to hydraulic braking is powerful and efficient. But there are disadvantages of both the braking systems and thus regenerative braking with proper research and proper risk should be used in vehicles.

Fig THS II shows about the ECB effect termed as eddy-current brakes shortens the stopping distance and thus the limitation of first graph is been solved and that shortcoming after getting solved helps many vehicles to help in the process of braking. Also, it has been shown in the second graph that the range of vehicle has been expanded enormously and thus can travel a longer distance and directly saving the fuel economy. The expanded regenerative range is 30-40% and so the vehicle gets boost in travelling a longer distance.

5.2) FUEL ECONOMY IS INCREASED:

As mentioned earlier due to the effective saving of energy the fuel economy is also boosted and it gives rise to one of the most efficient cars. Thus, in conclusion it can be said that regenerative braking system is “fuel-efficient”. The International Journal of vehicle design noted in 2011 that fuel consumption that was covering the NEDC (New European Driving Cycle) was improved to a great extent by 25%.

Also, another example is depicted here. The Delhi metro saved or conserved up to 90,000 tons of (CO₂) from being liberated into atmosphere by regenerating 112,400 megawatts hour of electrical energy with the proper use of regenerative braking system between 2004 – 2007. The most astonishing and mind-boggling thing about regenerative braking is that it can capture the more than half wasted energy and can put back to work in the vehicle and thus it has appreciable performance. The hydraulic braking system is much better and efficient and can produce much more effective gains and lowering the use of fuel by 30-45%.

5.3) WEAR OR TEAR AND FRICTION REDUCTION

In regenerative braking when the motor is getting or absorbing power from capacitor bank, it obstructs the alignment of wheels, which takes energy of the motion and giving that energy again to the capacitor. Thus, it reduces the wear and tear and so severe damage can be prevented and can make a smooth working cycle of the car

6) IS IT RELEVANT TO ONLY EV's (ELECTRICAL VEHICLES) OR ALL OTHER VEHICLES?

This topic also needs to be analyzed because the small cars or the cars which are for the family purposes can't be imbued with this system so by proper analysis, we can see that the cars which can have this type of braking system should have proper alignment of vehicles, stored capacitor banks and it is present only in the electrical vehicles. The family purpose vehicles are needed to have development to install this type of braking system. The electrical vehicles are the most appropriate for having the regenerative braking system.

There is no doubt regarding the retrieving potential/energy in the concept of regenerative braking method. As stated earlier, the speed at which battery charges is much higher than at the rate at which battery discharges and thus this gives rise to the small amount of energy that the battery can store during the rapid slowing of the vehicle. And thus, the **most important thing that comes into the picture is that we should not use regenerative braking system under fully charged conditions**. It is because the overcharging can damage batteries due to severe heating of the equipment, but the electronic drive circuit prevents the damage from overcharging. In this case the storage of energy is done in the capacitor bank and it is given to the vehicle afterwards when needed and also it is used in extending the range.

The formula to find kinetic energy is $0.5 * m * v^2$ and so the amount of kinetic energy that is retrieved from the vehicle is proportional to the vehicle's mass and the velocity at which the vehicle is going on. The mass is much higher in vehicles like car, trucks, JCB's, rollers and so they have more kinetic energy retrieved. In the city areas these heavy vehicles would gain a large momentum after acceleration though it has low starting speed, so during the decelerating, the kinetic energy is higher in electronic scooter which is travelling at the same speed. Thus, the efficiency of regenerative braking is much higher in electric cars, buses and vehicles. So, at last in conclusion it is to be said that this system is efficient for vehicles having high mass.

7) TYPES OF SYSTEM FOR STORING ENERGY

The storage capacity is more advanced in the new technologies mainly concentrated around ultra-capacitor, battery and converter needs to be joined to the vehicles of electric types. Various types of batteries such as nickel-zinc, lead-acid. A basic comparative study is shown of batteries.

Fig6) Life cycle, operating temp of different types of batteries

Battery type	Energy density	No. of cycles	Operating range Temp.
Ion -Li	110-160	500-1000	20 ⁰ -60 ⁰
Ni-Zn	60-85	1000	20 ⁰ -60 ⁰
Lead acid battery	110-160	400-1200	20 ⁰ -60 ⁰
Ni-Cd	45-80	2000	40 ⁰ -60 ⁰

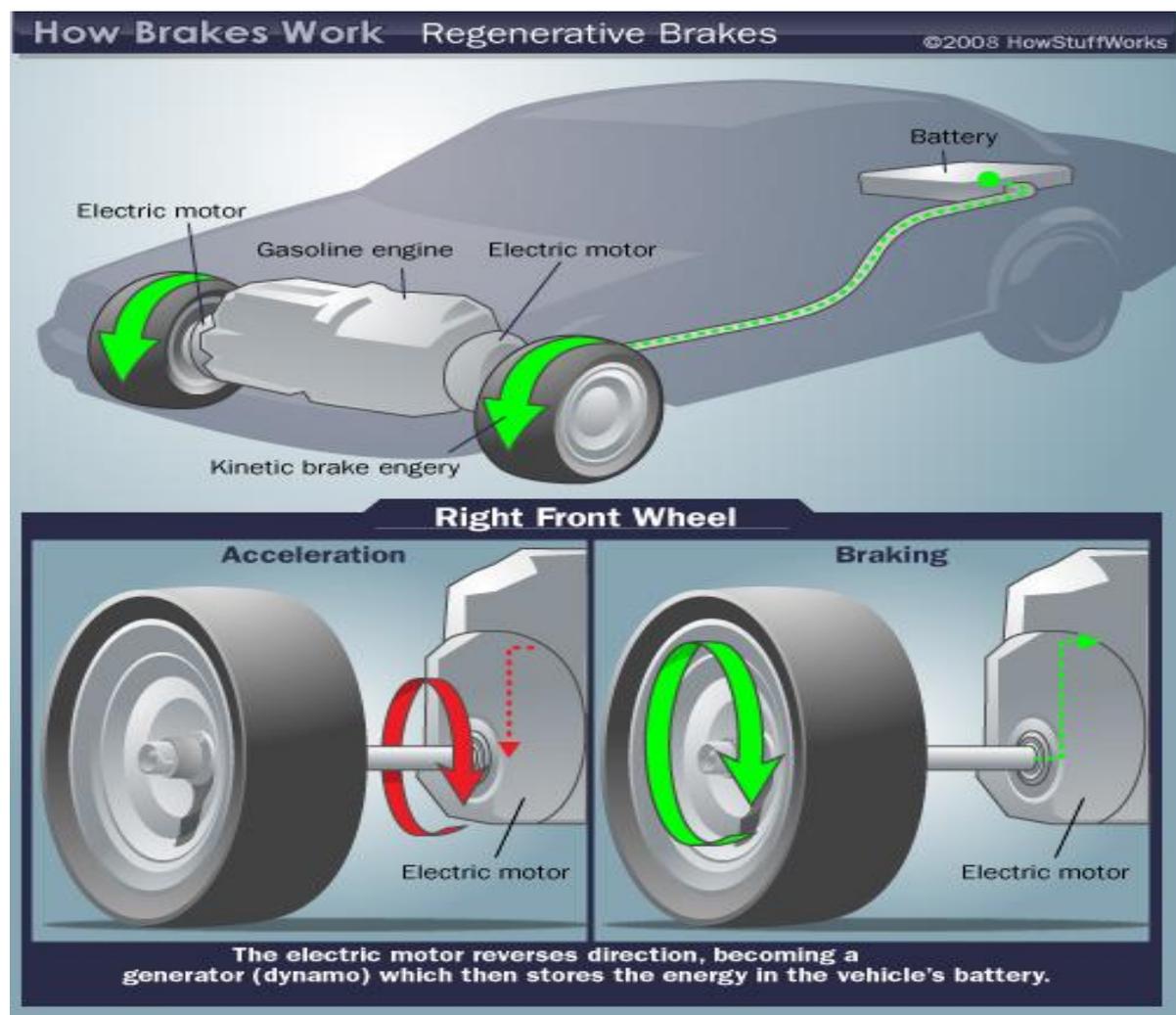
Source: - Wikipedia.org

Thus, we can observe that there are various types of battery available to store energy and can also be used in the place of capacitor. Thus, batteries are the most basic and important element in the regenerative braking system and can be considered a necessity to the system.

The battery should be connected properly in series with the system so that it can work or function properly. Although there are many ways to connect battery in the vehicle. To choose proper battery and the proper place to install the battery is also one of the challenging tasks that needs to be performed by the engineers.

8) IMPRESSION OF REGENERATIVE BRAKING SYSTEM

Fig7) Diagram of regenerative braking system in car

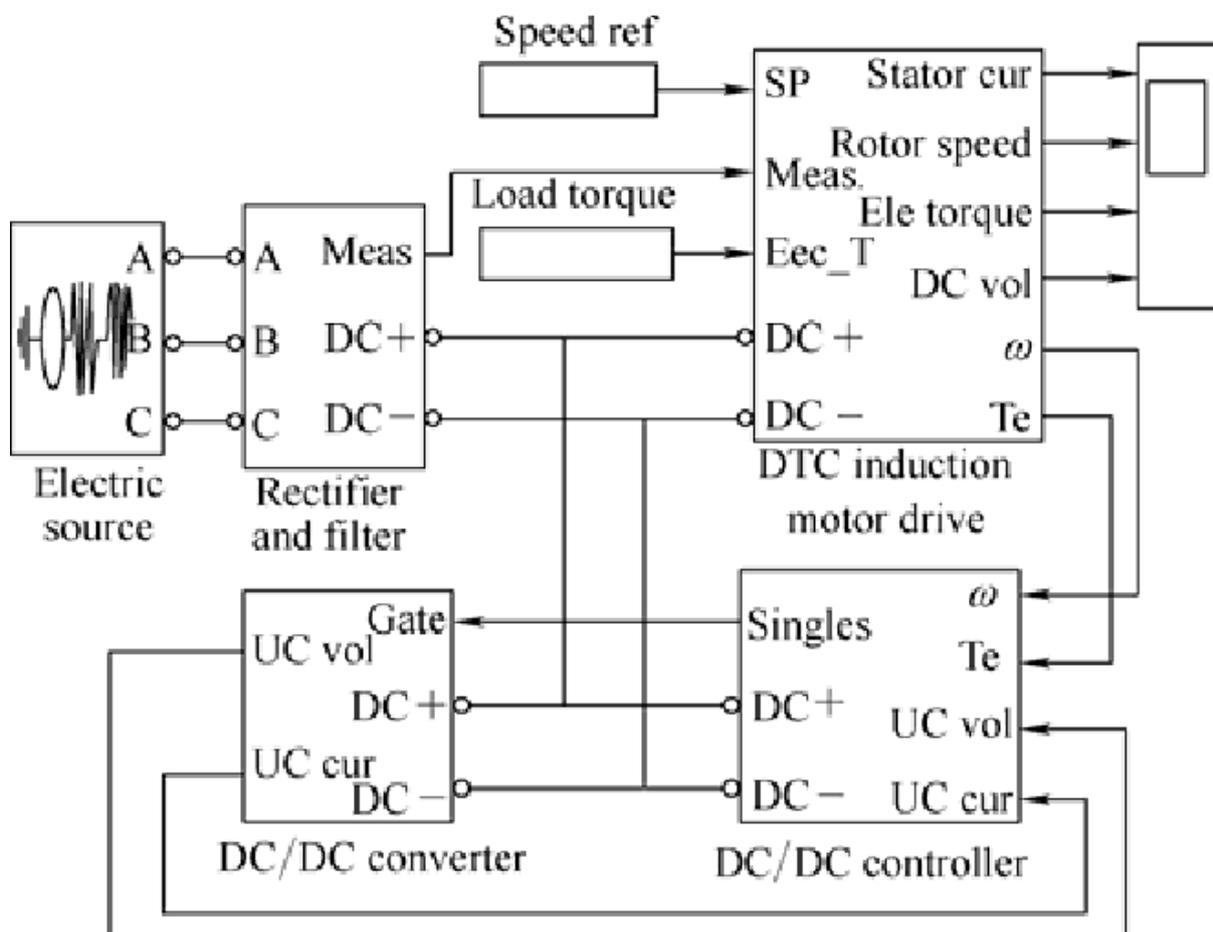


Source: - Images (how stuff works.com)

This simple diagram shows that how the regenerative braking system is able to retrieve some of the vehicle's kinetic energy and convert it to electricity or some other form of energy which can be used when needed later.

9) PRACTICALS TO BE PERFORMED (ANALYSIS IN DEEP)

Fig8) MATLAB system for regenerative braking system.



Source: - [www.MATLAB simulation of braking system images.com](http://www.MATLAB_simulation_of_braking_system_images.com)

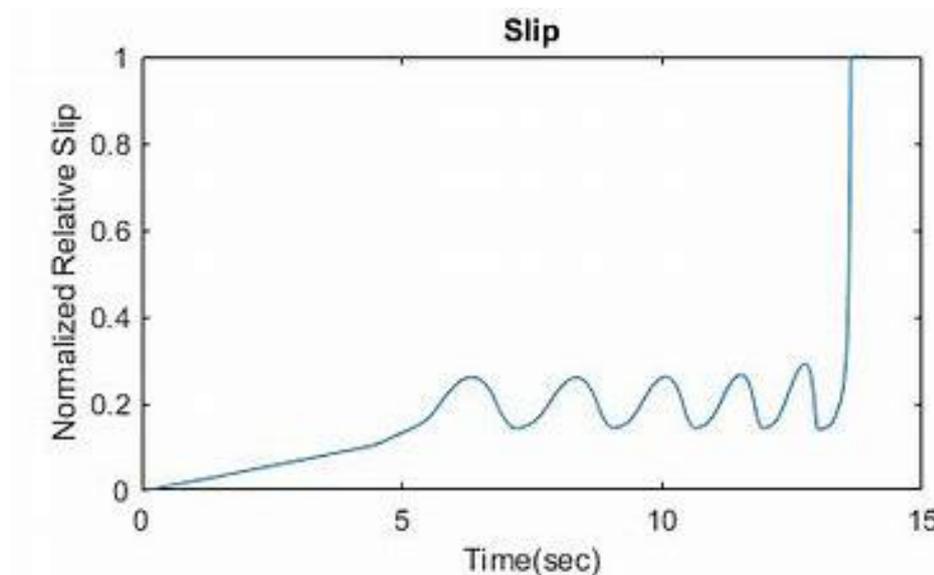
This is the MATLAB Simulink which is also known as the MATLAB model which is the perfect assumption that can be tested before performing on the car. This model gives us the perfect idea that how it works and can be proposed further to be more inferred.

Here, different angles and different measures are been given to the DC controller so it can work at different stages of the braking. At the first stage where brakes are applied the energy is stored in the capacitor and after the vehicle starts to accelerate or gain load then this energy can be re-used to give and consume it to the vehicle. Thus, this model leads to the real time application of regenerative braking system.

This MATLAB model as a result generates acceleration and braking at different cases and thus can be made to be a precise consideration to install it in electrical vehicles and can be further initiated to large vehicles like car, buses and trucks.

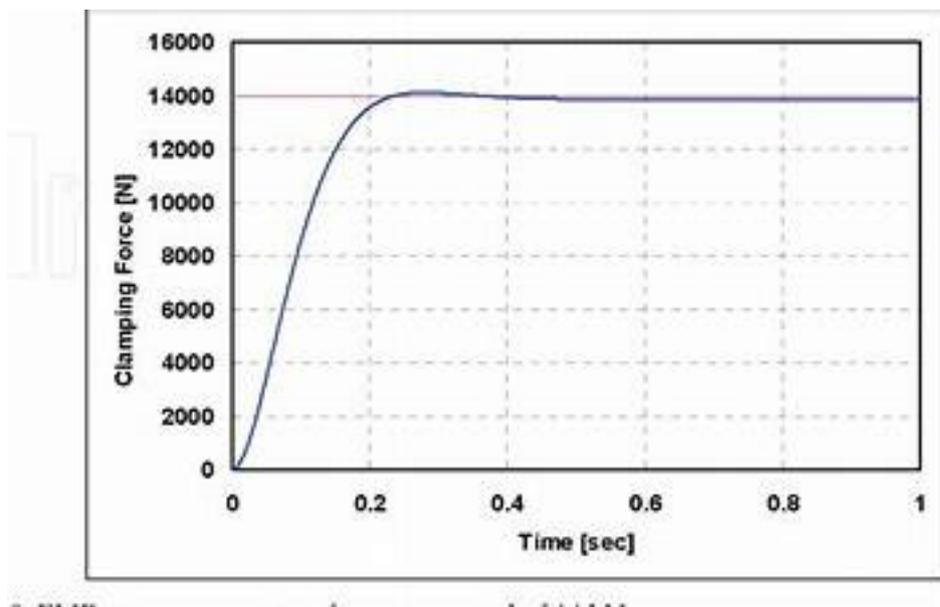
9.1) SIMULATION OUTPUT

Fig 9) Graph of relative slip vs normal slip



Source: - Wikipedia.org

Fig 10) Graph of force vs time period (in secs)



Source: - wikipedia.org

9.2) AVAILABLE ENERGY FOR BRAKING

Braking energy is the energy that is recorded when we apply brakes and so it's very important to estimate the actual braking for a braking instance which is given by the summation of rotational energy plus the translational kinetic energy from which the losses due to friction and rolling resistance are subtracted. Thus, from this formula we can find the energy that is available during the braking.

$$\Delta E_{a, b} = \Delta E_k + \Delta E_{rot} - V_{losses}$$

$$V_{losses} = F_{losses} * d$$

$$F_{losses} = F_d + \mu_r(mg)$$

Where,

F_d = aerodynamic drag force

μ_r = Co-efficient of rolling friction

d = Braking distance

V_{losses} = Work done

F_{losses} = Force at vehicle

10) MORE SPECIFICATIONS TO BE INCULCATED (According to Author's research)

10.1) The braking can be implemented in every vehicle to save energy and it should be connected to the rear vehicle axle and can be used effectively. For the front wheel there should be hydraulic braking.

10.2) A type of small storage battery should be connected extra to the rear vehicle so more of the dissipated energy can be stored.

10.3) The vehicle should try to avoid more braking if possible so that overheating of battery is prevented up to great extent.

10.4) An oil type cooling can be provided which can cool the overheating of battery and can prevent the harmful damage to the car.

10.5) More battery should be connected in series so it can provide effective storage to the braking system.

11) CONCLUSION

From the above research and whole analysis, we can infer and derive that the regenerative braking is one of the most effective method in the modern world. Every auto-mobile sector should include this type of braking for improving their car's quality and making them more efficient to the great extent. People should understand the importance of energy conservation and imbibe this system.

The regenerative braking system has the extra ordinary ability of saving or retrieving the waste energy to 8-15% and so improving the range of the vehicle to a greater extent. It is improved by the advanced and modern technologies and systems of power electronic components, bridge inverter, DC-DC converter and other resources. The research done above says a lot about this system and its advantages

to the world and auto-mobile industry. Also due to the sky touching petrol prices this system enables a highly efficient fuel economy and makes a vehicle better than the conventional method. The friction losses and other damages are also fully prevented and improves the fuel consumption by 33%.

The results derived above says that the power and energy is important and very useful and thus we need to use the regenerative braking system in electric vehicles.

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