Evaluation in Regenerative Breaking its Energy Efficiency and its Advantages in Electric Vehicles

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ABSTRACT

In this paper research is conducted on control of a regenerative braking system for electric vehicles. The evaluation methods of regenerative braking to improve electric vehicle's energy efficiency are discussed. In order to improve the efficiency of energy conversion and increase the efficiency of electric vehicles, there generative energy captured during braking process is stored in the energy storage devices and then will be re-used. Three control strategies called ''parallel control strategy'' and ''serial 1 control strategy'' and "serial 2 control strategy" are proposed as the comparative control strategy. In this paper there is a description of experiment done on electric vehicles. Road test is carried on in which information obtained is discussed. This paper consists of how the serial 2 control strategy offers higher regeneration efficiency than the parallel strategy and serial 1 strategy. Various energy storage devices like super capacitor battery and ultra capacitor are discussed in this paper.

Keywords*: Regenerative braking, Electric vehicles, Road test, Super Capacitor, Advantages.*

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1. INTRODUCTION

Due to the shortage of non-renewable resources, along with environmental issues, hybrid technologies and alternative fuels are being increasingly used. Automobiles are required to be more efficient. Many Control optimization are used to make automobile more efficient. Regenerative braking system (RBS) is widely used in these electric vehicles. The electric motor in RBS also works as a generator to convert the vehicle's kinetic energy into electricity, thus the wasted energy is stored in the battery for later use. About one third of the total energy generated is wasted, and is librated to the environment in the form of heat. Therefore, recapture of this wasted kinetic energy is necessary. If the regeneration and frictional braking are well-coordinated, high regeneration efficiency and good braking feeling are achieved.

The RBS has been already commercialized by automotive makers and component suppliers, such as Nissan, Toyota and BMW. There is conventional braking system known as non-regenerative braking system. There are three different braking control strategies for regenerative braking: parallel regenerative brake control strategy, and serial 1 strategy and serial 2 control strategy. The non-regeneration one, is set as a baseline, and only friction brakes are used during deceleration, the parallel regenerative brake control strategy features an easy implementation without any other hardware needs to be added, for the serial 1 strategy, it coordinates the regeneration and friction brake in real time, being advantageous over the parallel one with respect to the brake comfort and regeneration efficiency.

2. MECHANISM ANALYSIS

2.1 Configuration of the case-study electric vehicle

The configuration of the case-study electric vehicle is shown in Fig. 1. The vehicle is selected as a pure electric passenger car, which has the most typical configuration. The car is driven in front wheels by a permanent magnet synchronous motor, which can work in two states as a driving motor or a generator. A battery is electrically connected with the motor, and it can be charged or discharged during driving processes.

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292 – 297

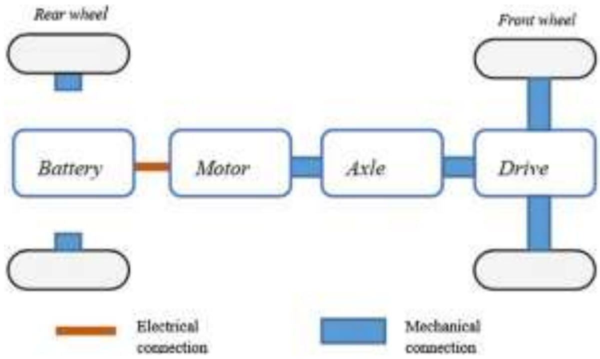

Fig-1: Configuration of the case-study electric vehicle.

2.2 Energy consumption of a non-regenerative braking electric vehicle

Assuming that the road is straight and dry with a high adhesion coefficient, and neglecting power consumption of accessories, high-level energy flow of electric vehicle is analyzed under the relatively ideal driving conditions as follows. The overall consumed energy E_drive which is utilized to drive the wheels can be calculated by

$$E *_{drive} = \int_{a\geq 0} P_{drive}\, dt$$

$$\text{P drive} = \text{fmgu} + \text{imgu} + \frac{C_D A u^3}{21.15} + \delta \text{mgu} \cdot \frac{du}{dt}$$

where P drive is the required power at driven wheels, f is the rolling resistance coefficient, i is the gradient resistance coefficient, m is the vehicle mass, CD is the coefficient of air resistance, A is the frontal area of the vehicle, δ is the conversion coefficient of rotational mass of power train, μ is the real-time vehicle velocity, a is the vehicle acceleration, and the a≥0 in the integral term indicates the driving processes (non-deceleration).

2.3 Energy consumption of a regenerative braking electric vehicle

Based on the same assumptions and environments described in Section 2.2, for an electric vehicle equipped with a regenerative brake, however, the energy flow, which is dual-direction one including propulsion and regenerative braking. According to the energy flow the energy E_drive consumed for driving the whole vehicle at wheels can be given by:

$$E_{drive} = E *_{drive} - \eta_d \eta_a \eta_{gen} \eta_{\text{charge}} \eta_{discharge} \eta_m \eta_{\text{a}} \eta_d E_{\text{regen}}$$

$$E_{regen} = \int_{P_{regen<0}} F_{mot\_brk}\, udt$$

where E_regen is the energy recovered by regenerative brake during the considered driving process, Fmot_brk is the braking force of motor, P_regen is the regenerative braking power at driven wheels, ηd is the efficiency of drive unit, ηa is the efficiency of axle, g_gen is the efficiency of the motor working as a generator, gm is the motor efficiency, g_charge and g_discharge are the charging and discharging efficiencies of the battery, respectively. Comparing the energy consumptions, the energy utilization of a vehicle reduced by regenerative braking can be given by:

$$\Delta E_{drive} = E *_{drive} - E_{drive}$$
$$= \eta_d \eta_a \eta_{gen} \eta_{\text{charge}} \eta_{discharge} \eta_m \eta_{\text{a}} \eta_d E_{\text{regen}}$$

The regenerated braking energy is converted from vehicle's kinetic energy to electrical energy during braking procedure, and stored in the battery. During non-deceleration processes, the recovered energy is eventually released from battery to power the vehicle. The contribution made by brake to energy utilization reduction of an electric vehicle can be obtained by:

$$\sigma = \frac{\Delta E_{drive}}{E*_{drive}} \times 100\%$$

3. ROAD TESTS UNDER CHINA TYPICAL CITY REGENERATIVE DRIVING CYCLE

To further the study of influence on vehicle's energy efficiency enhancement by the regenerative braking, vehicle tests are carried out on road under CTCRDC standard. The experiment vehicle is driven by a permanent magnet synchronous motor, which can work in two states as a driving motor or a generator. The experimental testing system is consisted of battery, motor, axle and drive unit. The battery is electrically connected with the motor, and it can be charged or discharged. Voltage sensor and current sensor are applied to acquire battery voltage and current respectively, slipping sensor is applied to acquire axle torque, pedal force sensor is applied to acquire force torque, and data acquisition equipment is applied to obtain kinds of data during the road test (see Table 2).

Test equipment	Accuracy	Unit
Voltage sensor	0.001	V
Current sensor	0.001	A
Pedal force sensor	0.1	N
Gyro	0.1	N/kg
Data acquisition equipment	0.1	N/m
Slipping sensor	1.0	r/min
Power source	1.0	W

Table-2: Key test equipment of the case study electric vehicle.

3.1 Road test results

In road test the control strategy is conducted every one CTCRDC cycle. The test is carried on electric vehicle. The test result obtained is for the three different strategy that is parallel strategy serial 1 and serial 2. During deceleration of vehicle eg- if the vehicle velocity is about 1.0 km/hr the regeneration braking will turn off which indicates that no regenerative energy is being stored i.e. no energy is being stored in the storage devices. As per the results the parallel control strategy is smaller than that of the serial 1 and serial 2 strategy. As the table shows, for the parallel regenerative braking case discussed here, the total recovered energy to the battery is about 0.206 kW h during one CTCRDC driving cycle.

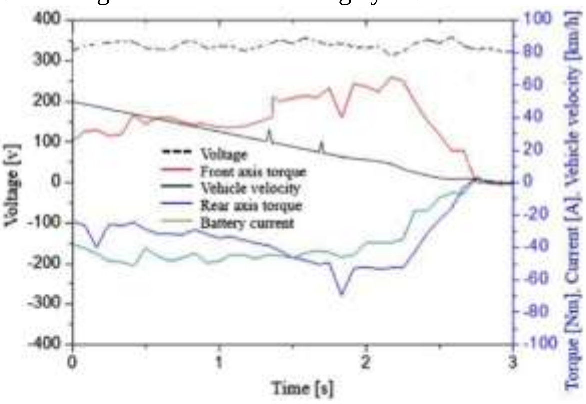

Fig-2: Test results of parallel regenerative braking strategy.

Fig 3. Shows the serial 1 regenerative braking control strategy in CTCRDC driving cycle. As the regenerative braking is on in this case the heat librated to the surrounding is being recovered, during deceleration of vehicle the kinetic energy of the wheels is being converted into heat energy, and this heat energy is converted into electricity due to the regeneration braking system. During deceleration the front axle torque shows negative value this means the kinetic energy is being recovered. With the current being negative the energy is being recovered in the storage devices. The energy recovery power of serial1 control strategy is lower than that of serial 2, during test of serial 1, at the time of deceleration the control strategy last for only 6 seconds. Accordingly to test result the energy recovered during serial 1 is 0.235kWh during one CTCRDC cycle

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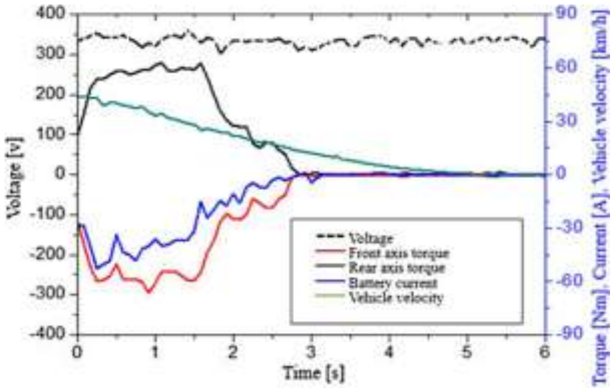

Fig-3: Test results of serial 1 regenerative braking strategy.

Fig-4 shows the test result of serial 2 control strategy. During one cycle of CTCRDC. The test is carried same as that of serial 1 strategy. During deceleration of vehicle in serial 2 the rear axle torque shows negative value which indicate the energy is being recovered in the storage devices. As the serial 2 strategy has high power recovery than serial1 strategy, the regenerative braking in serial 2 last for about 11 seconds. During the test result of the serial 2 the energy recovered in the storage device is 0.267kWh, which is much larger than that of parallel and serial 1 control strategy.

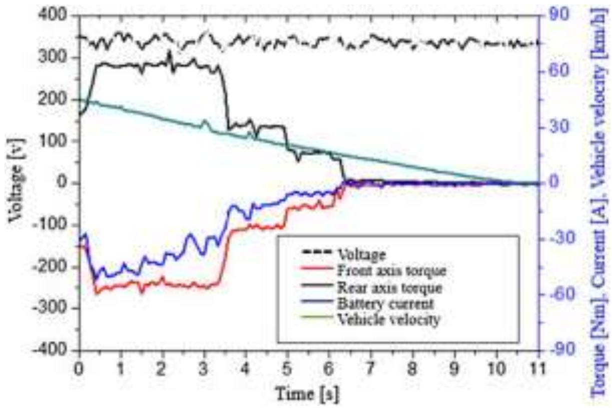

Fig-4: Test results of serial 2 regenerative braking strategy

4. ENERGY STORING DEVICES

4.1. Battery Data

One of the main accepts was will the batteries be able to absorb the small amount of energy generated by the brakes. Usually the energy is converted into heat and librated to the environment. The main question was how much allowance does the battery system will give for taking some of the work from braking system and recovering it back into the storage devices. Some of the calculations were done, so some relevant battery data is to be defined. The battery used in the system is lithium ion battery. The most relevant data is given below in table 3. It can be observed that there are both batteries in series and in parallel. In this case, there are 112 cells in series with a maximum charging voltage of 3.65 V each, which gives a maximum voltage of 408.8 V for the system. Analogously, batteries in parallels have their current capability multiplied by the number of cells in parallel. For this specific case the maximum charging current is 1 CA - 1 times the nominal current capacity of the cell, 3 Ah - totalling 420 A of maximum current capacity for the entire battery system. However, due to charging characteristics of these batteries, the controller limits the current transference, and the amount of regenerative braking current allowed by it is 200 A, which is the value used for the calculations.

Variable	Value
Type of battery	LiFePO4
Nominal Capacity	3Ah
Maximum charging current	1 CA
Maximum Charging Voltage	3.65V
Number of cells in parallel	140
Weight	90g
Total battery pack weight	1,411 kg
Total battery pack storage	172 kWh

Table-3: Battery Specification.

4.2. Super Capacitors Data

Super capacitor is the storing device. The main advantage of the capacitor is that it has a high power density compared to any other storing devices means it has the ability to accept and release charges at much faster rate. The capacitor can charge in less time and the only disadvantage is that is releases energy charge much faster rate. In order to investigate are the capacitor capable of absorbing regenerative braking energy. Because the amount of regenerative energy is very small. Some calculations are done to check the super capacitor is efficient or not. So capacitor data is to be defined. The chosen model to be analyzed was from Maxwell Technologies (Maxwell Technologies, 2011), model *BMOD0063 P125 B03*, since this model is specific for heavy-duty vehicle application. Some important data of this super capacitor is presented in Table below,

Variable	Value
Type of Capacitor	Super capacitors Module
Rated Capacitance	63 F
Rated Voltage	128 V
Resistance	18 μΩ
Maximum Continuous Current	240 A
Peak Current, during 1 second	1,900 A
Weight	60.5 kg

5. ADVANTAGES

From the provided Information of battery and super capacitor, we come to know that capacitor is a great and useful energy storing device with provides a great charging rate and gets fully charged by very less time

It is observed that the battery charging energy required for battery is much more than a super capacitor. By RBS the efficiency of vehicle increases from a greater extent. Lowering carbon emissions .Main reason is that the wasted energy that is no more useful can be re-used and is used to charge the battery of the vehicles. Ultra capacitors or super capacitors are the devices that can accept and release charge much more quickly ex. The Mazda unit can accept a full charge in just 8-10 sec. The capacitor may take upto about 113s when the load is minimum about 18A.

6. CONCLUSION

Vehicle road test were carried out in CTCRDC driving cycle under the influence of china, the results obtained for the three control strategy were good for the serial 2 strategy. The test result showed that under the CTCRDC, the contribution ratio made by the regenerative braking to energy transfer efficiency improvement and to regenerative driving range is upto 41.09% and 24.63% respectively .In case of emergency brakes the braking force mainly comes on front wheels. The regenerative braking system needs a specific velocity of the vehicle or the vehicle need to in specific limit of speed. If the speed of vehicle is too low then the regenerative braking will not work because very ample amount is energy is generated with is not able to charge the battery. Another main aspect is the regenerative braking energy efficiency also varies from driver to driver. The force acting on the brake pedal is one of the important factor that affect the regenerative braking system. If we can combine the front and rear axle braking force for energy conservation then the energy recovery effect will be better. The energy efficiency in electric vehicles can be increased by using capacitor. It can be believed that use of a super capacitor can increase the overall performance and efficiency of the system. From the above information we can conclude that if battery is in electric vehicles the time required to charge the battery is very more. If we use capacitor the time required to charge the battery is very less but due to the disadvantage of the capacitor it is not used by many manufacturing companies. Now research is going on to implement the battery and capacitor in one unit. To combine the advantages of the battery and capacitor. The factors that will increase the performance is that the advantage of battery that is discharging the battery at very slow rate and the advantage of capacitor that it will charge in very less time. By doing this we can get a storage device which will change the future of the electric vehicles.

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