

Comprehensive Analysis of Braking Energy Recovery System for New Energy Vehicle

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Abstract. The braking performance of a vehicle not only has a direct impact on the safety of the vehicle, but is also closely related to the comfort of the driver and passengers. As the amount of new energy vehicles (NEVs) constantly rising, more and more people are choosing new energy vehicles as a way to get around, and as a direct factor in determining the braking capability of a vehicle, the design of the braking system of a modern NEV is crucial. In normal operation, braking energy recovery (BER) is the biggest advantage of NEVs that distinguishes them from conventional vehicles. As an essential way to save energy in electric vehicles (EVs), this technology uses the motor to recover part of the energy from braking, which can effectively enhance energy utilization and the driving mileage of the vehicle.

Keywords: Brake energy recovery, energy-saving, energy storage system, new energy vehicles.

1. Introduction

With the continuous increase of car ownership in recent years, the traditional fuel vehicles, which are the mainstay of the population, have led to the massive consumption of non-renewable resources such as petroleum fuels, and in addition, the unrestricted emission of large quantities of vehicle exhaust not only seriously endangers human health, but also causes bad pollution of the atmosphere. In this environment, the development of new energy vehicles powered by clean energy is gradually gaining attention from all countries and is the focus of future development of the automotive industry worldwide.

Vehicles that use non-conventional automotive fuels as a source of power, or new on-board power units, are called new energy vehicles (NEVs). Pure-, hybrid- and fuel cell-electric vehicles all fall into the category of NEVs [1]. The huge advantages in terms of structure, emissions and technology are important reasons why they are the way forward for vehicles, but the short range of new energy vehicles is also one of the main factors limiting their development.

A car under braking is subject to rolling resistance (RR), air resistance (AR) and braking force (BF). Here, the braking force is composed of mechanical friction BF and electric mechanism BF. Mechanical friction BF will convert the kinetic energy into heat energy, which will be dissipated in the air, meaning that this part of the energy cannot be recycled, and the energy lost by rolling resistance and air resistance also cannot be controlled and recycled, only the motor braking energy can be recycled. [2]. Conventional vehicles use purely mechanical braking, which causes a significant proportion of the vehicle's energy to be lost through friction in the form of heat during the braking process, whereas NEVs can incorporate braking energy recovery (BER) technology to attempt to reserve the energy from this process and reuse it in the on-board battery.

BER systems for new energy vehicles can effectively improve vehicle energy efficiency and extend the mileage of the vehicle [3]. In addition, the BER system also has the engine braking function of a conventional fuel car. When the vehicle is braking, without the counter-dragging effect of the generator, all the braking load is applied to the braking system (BS), and the thermal load on the BS will be very large, which will easily lead to a reduction in the braking efficiency of BS, especially

when continuously going downhill. It is also important to reduce the load on the BS to improve safety and brake life. At present, the research on BER control is relatively weak and cannot be fully optimised in practical applications. Based on the characteristics of NEV use scenarios, the optimisation of BER strategies can recover the energy originally lost in braking and ensure the braking effect, while the BER control can effectively increase the vehicle range.

This paper introduces the structure and principle of the BER system for new energy vehicles, compares the characteristics of supercapacitors and batteries and their applicability in the BER system, and discusses the BER logic for NEVs in different scenarios.

2. State-of-the-art Energy Storage Techniques

2.1. Supercapacitor

Compared to other traditional energy storage devices such as batteries, supercapacitors have a high-power density. As shown in Fig. 1, supercapacitor uses the double layer of electrode electrolyte cross interface or rapid and reversible redox reaction at the electrode wide interface for energy storage, as shown in the figure, which is made of porous activated carbon material with very large specific area into porous carbon electrode, while filling electrolyte solution between the electrodes, when voltage is applied at both ends of the electrodes, the relative porous electrodes will gather positive and negative electrons, and this electrolyte solution will get positive and negative The positive and negative ions in the electrolyte solution will be collected at the interface between the positive and negative electrodes due to the electric field, thus forming a double electric layer between the electrodes and the electrolyte solution.

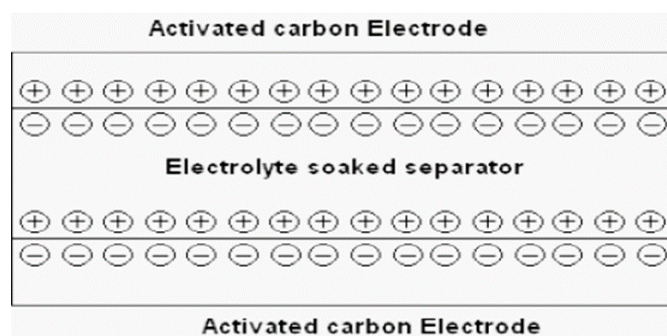


Fig. 1 Internal structure of a supercapacitor

Due to its low internal resistance, it can store and release charge quickly at the electrolyte interface and in the electrode material itself, so its output power can be up to several kilowatt kilograms, which is tens of times higher than the general battery. Supercapacitors have a long charge/discharge cycle life. As there is no electrochemical reaction during charging and discharging, only ion and charge transfer process, there is almost no loss, so the cycle life can reach tens of thousands of times, which is much higher than the general battery. Another important feature of supercapacitors compared to general batteries is that they can be charged and discharged at high currents. This feature is directly determined by the working principle of the supercapacitor itself, which enables the supercapacitor to finish charging in a very short time and to carry out high power output in a short time, which is impossible for the battery. Because the leakage current of super capacitor is very small after charging, it has a long storage life. However, as the electrolyte inside the supercapacitor is relatively stable, and the internal charge migration movement is generated by the electric field, no electrochemical reaction occurs, so its life span is almost unlimited. Compared with battery, supercapacitor has high power density, up to 5kW/kg, which is more than hundreds of times than battery; supercapacitor can be charged and discharged nearly hundreds of thousands of times, which is much higher than other energy sources; supercapacitor is natural and pollution-free material, which is friendly to the environment; good temperature characteristics, which can work between -40° and 70° . Based on the operating characteristics supercapacitor can provide instantaneous peak power in the sudden

acceleration and deceleration and braking of EVs, fully meeting the requirements of EVs for high specific power. Its disadvantage is mainly the low specific energy. Therefore, the future dual energy source structure combining battery and supercapacitor can give full play to the advantages and disadvantages of both and meet the power source requirements of high performance electric vehicles [4].

2.2. Battery

The battery is generally made up of one or more single cells connected in series and parallel. It works on the principle of electrochemical reaction, converting chemical energy into electrical energy, and is the most commonly used energy source for electric vehicles. The following are a few batteries with different chemical reaction principles. The main chemical reaction substances in lead-acid batteries are metallic lead and sulphuric acid, which are used in the battery cars that can be found everywhere on the market. The disadvantages are obvious: low specific power and short cycle life, with the average battery being charged and discharged 800-1000 times and used for about 2 years [5].

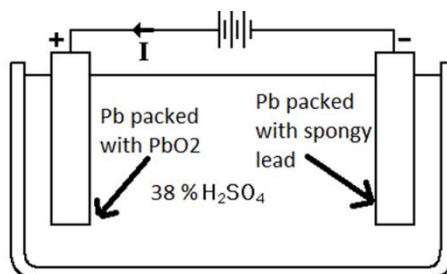


Fig. 2 lithium iron phosphate batteries

Lithium batteries are more expensive than lead-acid batteries and are not yet very popular, but are a more intensively researched type of battery. Its disadvantages are high production costs, poor safety, the risk of explosion and sensitivity to temperature conditions [6-8]. Metal-air batteries are, as the name implies, a new type of high-performance green battery with metal and air as the reaction substance. But the corrosion of the battery electrode and self-discharge phenomenon, which is its most fatal drawback, is the current technology research in. Nickel-chromium batteries are the earliest batteries used in mobile phones, computers and other electronic products, which have the advantages of high current charging and discharging characteristics, small internal resistance, very small changes in terminal voltage during discharge and simple maintenance. The "memory effect" and cadmium pollution are important factors that hinder its development.

The battery is characterised by high energy density, low power density and short cycle life. They are not good at high power output in short periods of time. In urban conditions, due to topography, traffic and other factors electric vehicles often need to start, stop, accelerate and decelerate frequently. This will not only affect the range of the EV, but also shorten the cycle life of the battery, which will greatly increase the cost of using and maintaining the electric vehicle.

The hybrid supercapacitor-battery energy storage device can complement the advantages of the supercapacitor and the battery pack. The supercapacitor provides the electric energy for the electric vehicle under conditions such as starting, accelerating and uphill, while the battery provides the electric energy for the electric vehicle under low load conditions such as smooth driving and high-speed cruising [9].

3. Braking Energy Recovery System

3.1. Working Principle

A car with braking energy recovery technology can transfer the inertia generated by braking to the drive motor through the drive wheels and transmission system, at which time the drive motor switches to generation mode and the braking energy or coasting energy drives the drive motor to generate

electricity, converting the kinetic energy of the car into electrical energy, which is then converted into chemical energy and charged by the DC/DC conversion circuit to the on-board battery, thus realising energy recovery. Meanwhile, the drive motor generates resistance torque, which acts on the drive wheels through the transmission system to achieve the braking effect [10]. The controller coordinates the proportion of motor BF and mechanical BF to finalise the braking of the vehicle. The BER model in NEV is shown in Fig. 3.

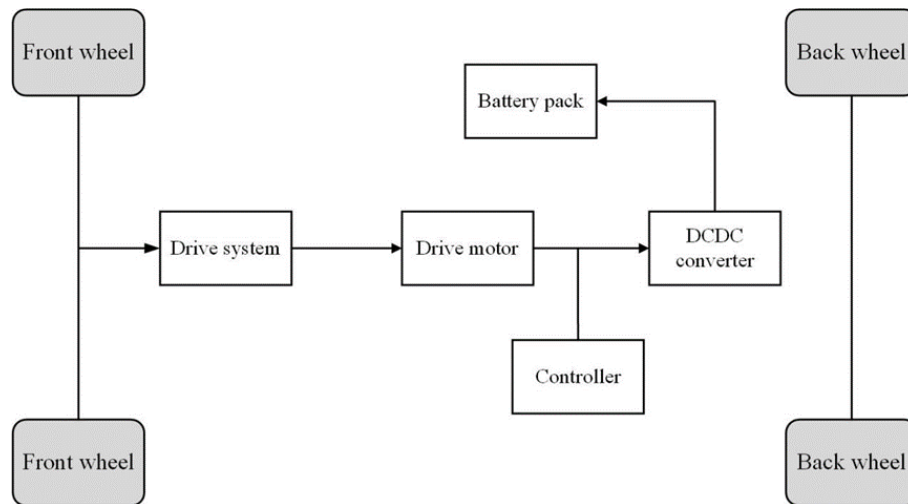


Fig. 3 System diagram of braking energy recovery system for new energy vehicle

In the normal motor feed-back braking simply rely on the motor to generate the feed-back torque does not meet the total braking demand, the vehicle's drive system must be involved in the braking process, which can not only ensure the braking performance, but also the comfortability and smoothness.

The hydraulic assist system provides greater auxiliary power to the vehicle than the electric motor BER system, which can solve the problem of insufficient power in EVs, and it has a higher energy use efficiency, the storage and release of energy is much faster than the battery, the recovery of energy is also more, relatively improve the vehicle range [11], [12].

Most small cars today use hydraulics to achieve the braking effect. The use of hydraulic braking means that the force required to apply the brakes is transmitted via a fluid. The hydraulic braking device converts pedal force into hydraulic energy in the form of a simple transmission mechanism with a direct mechanical connection. When the driver depresses the brake pedal (BP), the piston of the master pump is pushed forward and the pressure of the brake fluid in the master pump rises, entering the sub-pump of each wheel through the oil pipe and pushing the piston of the sub-pump outwards, realising the transfer of the force of the foot on the pedal to the wheel brake and pushing the wheel brake to apply the brake. If driver eases off the BP, the master pump piston returns under the action of the oil pressure and return spring, and the sub-pump piston and wheel brakes return to lift the brake on the wheels. Cross-piping is commonly used in domestic cars, so that when one pipeline leaks, the other pipeline still acts as a brake, and the braking force is also more balanced, which can effectively avoid brake runout.

As the voltage of the battery varies in a certain range with the power and is closely related to the load, the power battery in the main powertrain needs to be regulated by a DC/DC converter, which then drives the motor and supplies power to the high-voltage appliances through an inverter [13]. It is the most basic type of power converter for transforming electrical energy and voltage.

The majority of onboard electronics and auxiliary power sources are powered by a 14V battery system [14]. Due to the limited storage capacity of batteries, traditional vehicles can convert energy using a generator, however electric vehicles must draw power from the power cell, necessitating a high-efficiency step-down DC/DC converter with a wide variety of inputs and outputs.

3.2. Logic Setting For Braking Energy Recovery

3.2.1 Brake system structure settings

The distribution of BF is mainly divided into the distribution of front-back wheels BF and the distribution of mechanical BF and motor regenerative BF [15].

In order to ensure the safe braking of the car, the front-back wheels BF should be distributed according to the ideal BF distribution curve, which can make the pure electric car achieve a better braking effect in the braking process and finally reach the maximum braking torque strength that can be provided by the driving surface, which can ensure the shortest braking distance and the best braking performance to a large extent [16]. Here, the ideal BF distribution curve for the front and back wheels can be expressed as

$$F_{\mu r} = \frac{1}{2} \left[\frac{mg}{h_g} \sqrt{b^2 + \frac{4h_g L}{mg}} - \left(\frac{mgb}{h_g} + 2F_{\mu f} \right) \right] \quad (1)$$

When a car is braking, once the braking force reaches any point on the I-curve, it means that the front and back wheels will lock up at the same time. The ideal brake force distribution control strategy takes the I curve as the main basis for brakeforce distribution, while taking into account braking safety and energy recovery efficiency [17].

As shown in Fig. 4 , when the braking strength is lower than the threshold (0.1 in this thesis), the demanded braking force is smaller and the motor can complete the braking task alone, which means that the mechanical friction braking system of the front and back wheels is not involved in braking and the braking force is all supplied by the motor, at this time the braking force is distributed along the OA curve in the figure.

When the braking strength is higher than 0.1, the mechanical friction braking system also participates in braking, and the two systems coordinate with each other so that the front and back braking forces are distributed according to the I curve. If the motor cannot provide the required braking force to the front wheels alone, it provides the maximum braking force and the mechanical friction braking system provides the remainder.

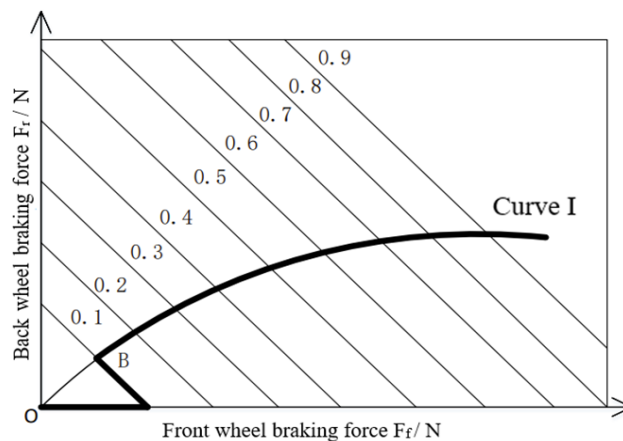


Fig. 4 Curves of ideal front-back wheels BF distribution control.

3.2.2 Brake Energy Recovery System Workflow

(a) *Combined supercapacitor and battery drive mode*: Takes advantage of the fast discharge and high specific power of the supercapacitor to start the vehicle in a combined supercapacitor and battery drive mode. After the fuel cell has warmed up to normal operating temperature, the decision to start the fuel cell is based on the system power demand and the state-of-charge (SOC) value of the auxiliary energy source. When the SOC value of the auxiliary energy source is lower than the desired value and the system power demand is between the minimum and maximum output power of the fuel cell, the power output of the fuel cell should not only meet the power requirements of the vehicle but also charge the auxiliary energy source. In the charging process, the supercapacitor should be charged first.

When the SOC value of the supercapacitor returns to the desired value, then the battery is charged to bring the battery power back to the desired value [18].

(b) *Combined fuel cell and battery drive mode*: When the SOC value of the battery pack is higher than the desired value, and also in order to control the battery charge state is always near the desired value, the remaining shortage of power to be discharged from the battery is output by the fuel cell and should fall within the effective working range of the fuel cell. The external discharge power of the battery is determined by the difference between the current SOC value and the desired value.

(c) *Regenerative braking mode*: When the vehicle decelerates or brakes, if the braking intensity is low and the braking power of the electric motor can meet the braking requirements, then the electric motor braking is used alone. If the braking intensity is high the braking power of the electric motor cannot meet the braking requirements using a combination of electric motor braking and traditional mechanical braking.

3.2.3 Factors influencing braking energy recovery systems

If we want the vehicle work steadily while the vehicle during braking, it is necessary to reasonably distribute the front and back wheel BF according to the actual vehicle model, on this basis, the electric and mechanical braking force are distributed for different braking conditions to ensure that the electric braking force does not exceed the maximum braking force that can be offered by the electric motor, so as to maximize the amount of BER.

Motor performance is key to energy recovery. During the charging of the motor to the battery, the motor does not fully recover the braking energy due to rotor-stator resistance, copper losses and heat losses, so the amount of regenerative braking force is influenced by the power generated by the motor. In high intensity braking, the motor and friction brakes need to be involved in conjunction with each other in order to ensure braking safety, so the energy recovery control strategy is developed with the motor performance in mind.

The energy recovery rate is inversely proportional to the magnitude of the braking force and the initial speed of the electric vehicle. Different driving conditions require different numbers and lengths of acceleration and deceleration, which in turn affects the amount of energy recovered. Urban circulation conditions with high traffic flow and many traffic lights require frequent braking and a long braking time, which can recover more energy. Highway conditions require less braking, and if braking is done it is mostly for emergency braking, so less energy can be recovered.

The energy recovery rate is proportional to the magnitude of the driving surface adhesion coefficient [19]. Different road surface adhesion coefficients affect the magnitude of braking intensity during braking, and thus affect the BER. For example, a high coefficient of adhesion on dry asphalt and concrete will result in greater braking force and better directional stability when braking.

The amount of energy recovered is also limited by the type of energy storage (battery type or structure) and the charging capacity of the battery [20]. With the energy storage method in place, it is necessary to avoid damaging the battery and shortening its life due to excessive battery charging power during braking. According to the regulations, the recovery system is only triggered to recover energy when the battery SOC value is low. Therefore, braking energy recovery needs to take full account of the current size of SOC to recover energy reasonably.

3.2.4 Safety logic in braking energy recovery systems

When the driver start to brake, the hydraulic brakes (hydraulic servo braking system) go into action in real time according to the brake pedal force, through the trip simulator and other parts, followed by the BER system. As the time the car is nearing stop moving, the BER system braking force becomes zero.

The energy storage system has strict requirements for the parameters of each component and the energy recovery solution should meet the full vehicle operation strategy. As the main power supply device of the NEV, the lithium battery needs to be deployed for power

Based on the principle of constant power ratio to achieve energy allocation. If the energy allocation of the power supply is unreasonable, it will easily lead to overload causing charging and discharging

faults, low efficiency of the battery storage power and easy depletion of the power, which will lead to accidental stopping in serious cases and cause potential accidents. To solve this problem, on the one hand, the battery itself can be upgraded to achieve sufficient drive power, and on the other hand, the stability of the maximum discharge current can be optimised by improving the energy interaction scheme. In the braking energy recovery process, the supercapacitor works in conjunction with the battery to determine the power demand according to the battery's operating status and to trigger an active charging response from the battery when the power is too low. In the energy storage system, the battery SOC is the main criterion for processing, and when the threshold is outside the limit, the hybrid system uses the battery as a protection state and the traction motor will operate in a low-power form [21]. During braking, the mechanical power generated by the motor will be compared with the discharged power of the battery in real-time feedback. When the motor power is low, the battery is replenished and the energy conversion is multi-directional, with both energy transfer between the battery and the supercapacitor and power transfer from the battery to the motor.

In the braking system, it must be judged whether the vehicle is driving on a good road surface or a bad road surface, which means that it must be judged whether the fluctuation of the BER torque reaches a sufficiently small state (the state of sufficiently small fluctuation of the brake master pump pressure) or whether the fluctuation of the braking energy recovery torque increases state (the state of increased fluctuation of the brake master pump) due to the increase of the road resistance. When the vehicle is driven on a bad road surface, the state of increased fluctuation of the BER torque is judged according to the resistance until the braking energy recovery is prohibited and only hydraulic braking is performed to ensure the braking safety of the vehicle. The above judgement is made by the brake energy recovery electronic control unit. That is, the Braking Energy Recovery ECU makes a judgement about whether the vehicle is driving on a good road surface or a bad road surface based on the output information from each wheel acceleration sensor.

4. Summary

In this paper, the braking energy recovery technologies are comprehensively reviewed in terms of the principles, structures and corresponding energy storage systems.

New energy vehicles are subject to increasingly intensive research, and lithium batteries are widely used due to their light weight, high energy storage, high power and non-pollution characteristics. In addition, supercapacitors have the advantages of long life, high power density and fast charging/discharging. A hybrid system combining lithium batteries and supercapacitors can effectively reduce the charging/discharging rate of batteries and extend the battery life.

There are many elements that affect the recycling efficiency of braking energy, such as the motor power, different driving surfaces, initial speed, energy storage methods and battery charging capacity will have a certain impact on braking energy recovery. Based on the characteristics of new energy vehicle use scenarios, the optimisation of braking energy recycling strategies and the comprehensive consideration of influencing factors enable the braking energy recycling percentage to be improved to more than 20%, or even to a higher level. Therefore, in the future research system of new energy vehicle technology, further research on brake energy recovery is needed to further improve the energy use efficiency of new energy vehicles and make positive contributions to the healthy development of the new energy vehicle industry and ecological environmental protection.

The more demanding the base conditions are, the higher the recovery rate of the BER strategy. For the development of pure EVs, improving the base conditions also means increasing the overall vehicle cost, extending the development cycle and increasing the development cost, so in engineering practice only the most critical base conditions can be improved.

Under the precondition of guaranteeing braking safety, the front and back wheel braking forces are allocated based on the ideal braking force distribution curve; a BEV strategy is proposed to complete the distribution of mechanical braking force and regenerative braking force to the motor by reasoning out a suitable regenerative braking force distribution coefficient.

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