Comprehensive Analysis for Braking Energy Recovery Strategies of Hybrid Electric Vehicles

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Abstract. The recovery of braking energy is a very important technology for hybrid electric vehicles. When the internal combustion engine vehicle decelerates to a stop, the vehicle's kinetic energy is converted into thermal energy, which is released into the atmosphere through the braking system. In hybrid and pure electric vehicles, wasted kinetic energy is converted into electricity, stored in cars and further powered by energy storage systems. In this paper, the energy storage systems of many kinds of hybrid electric vehicles are described in detail, and the future development of hybrid electric vehicles is analyzed.

Keywords: Hybrid electric vehicle, Braking energy, Recovery system, Applications.

1. Introduction

The global automobile industry faces a number of common challenges, including a shortage of combustion materials, environmental contamination and climate warming caused by carbon dioxide emissions. Governments and industries have worked out their own sustainable development strategies to improve their international competitiveness in the future. Of these, the most significant is undoubtedly the development of new energy vehicles. As an important representative of new energy vehicles, electric vehicles have broad development prospects, not only save energy but also protect the environment, and is the inevitable choice for the sustainable development of the international community [1].

The electric vehicle is different from the power circuit of the internal combustion engine, which not only has the performance of the internal combustion engine but also has the basic characteristics of the electric vehicle. As the key technologies of high-performance batteries needed by fuel cell electric vehicles and pure electric vehicles are not yet mature, it is difficult to achieve their development goals for a long time. HEV (hybrid electric vehicle), which can fully reflect the advantages of pure electric vehicle and traditional internal combustion engine vehicle, successfully avoids the key technical bottleneck of high-performance battery, and also can meet the comprehensive requirements of low fuel consumption, low emission, high energy saving and environmental protection. It has become the focus of electric vehicle development and research.

HEV refers to the car that carries two kinds of power sources, fuel engine and motor, according to the driving needs of the car, or using different power sources at the same time or separately. According to the type, quantity and connection relationship of HEV parts, it is mainly divided into the following three categories: series type, parallel type and series-parallel type.

In addition to the structural differences, there is an additional feature: hybrid cars have regenerative braking, which is one of the biggest differences from previous fuel vehicles. HEV calls the process of recovering and storing the kinetic energy of the vehicle during braking as regenerative braking, and the stored energy is called regenerative energy [2]. The speed of the vehicle driving in the urban area is generally low, and the load rate fluctuates greatly, which requires constant starting and braking. Relevant research data show that the energy consumed into the air in the form of thermal energy is about half of the total driving energy in the braking process. If the energy lost during braking can be stored and reused, the driving mileage of the car will be greatly improved. According to relevant data,

through the regenerative braking energy recovery system, the driving range of electric vehicles can be increased by at least 10% and 30% on a single charge, and the mileage can be increased by 10% and 20% by renewable energy. Therefore, it is important to study the energy recovery of regenerative braking system to save energy and improve the energy efficiency of HEV. At present, under the actual situation that the key technology of high-performance battery of electric vehicle has not made great progress, the regenerative braking energy recovery device can prolong the driving range of HEV and improve the energy efficiency. The research results on braking energy show that regenerative braking performance can improve the fuel efficiency of HEV by more than 20%, and the energy recovered by regenerative braking performance of pure electric vehicle can increase its driving range by about 20%. Therefore, regenerative braking technology not only saves energy, but also protects the environment, and has significant economic and social value [3].

2. Classification of hybrid electric vehicles

The arrangement shown in figure 1 is a series hybrid power system. The series type is the simplest structure in the hybrid power system, which relies on the operation of the engine to power a generator and transmit the resulting electricity to the battery, then transmits it to the motor into kinetic energy, and finally drives the car through the transmission system.

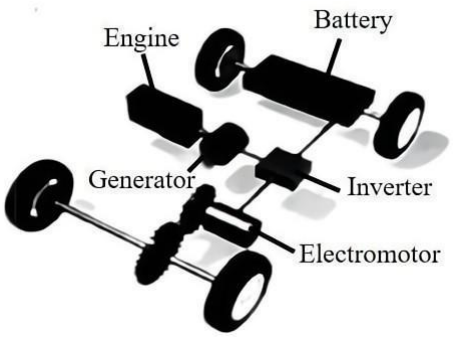


Figure 1. System diagram of series hybrid electric vehicle

From the point of view of the driving mode, the structure takes the power generation of the engine-generator set as the main power source, the electric energy of the power battery pack as the auxiliary power source, and the drive motor is the only driving mode. The structure of the drive system is relatively simple, and its dynamic characteristics are close to those of EV. The advantage of this arrangement is that it can realize the feedback recovery of braking energy, but there exists the energy conversion from mechanical energy to electrical energy, from electrical energy to mechanical energy, and the whole vehicle is relatively inefficient, which is precisely the biggest disadvantage of the series structure. secondly, in the process of vehicle driving, the engine cannot provide driving force according to the operating conditions of the road. In addition, the mass of the three powertrain is very heavy, the volume is also very large, and the power battery pack also occupies a lot of space, which directly leads to the difficulty of this arrangement in small and medium-sized models. Usually, it can only be used on models with large layout space [4].

The arrangement shown in figure 2 is a parallel hybrid power system. The structure is a PHEV drive system which is composed of engine, generator or drive motor in parallel. From the point of view of the driving mode, what is different from the series type is that the energy output of the engine and motor is used to drive the whole vehicle. According to the different control strategies and working conditions, four driving modes can be realized. In other words, the main energy source of the parallel hybrid electric vehicle is the engine, and the motor drive is used as an auxiliary, which can improve the power performance, emission performance and economy of the whole vehicle.

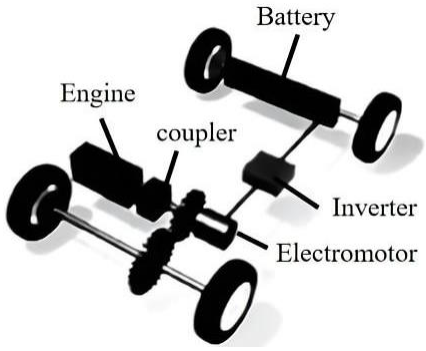


Figure 2. System diagram of parallel hybrid electric vehicle

The parallel system has two different structures before and after the gearbox according to the arrangement of the motor. The previous arrangement of the gearbox can replace the starter on the traditional engine to realize the automatic start and stop of the engine. The advantage of this arrangement is that the starting torque of the motor output is maximum, which achieves the starting condition of the engine. At the same time, the motor itself can realize the function of separate drive, power drive or generator. The disadvantage is that the input or output power of the motor has to go through the gearbox, so the power output of the motor is reduced and the feedback energy is also reduced.

The arrangement behind the gearbox can realize the functions of pure electric drive, electric power assist and braking energy recovery. The advantage of this arrangement is that the motor can transfer the power directly to the wheel; in the pure electric drive mode, the gearbox can work in neutral; when the vehicle is running normally or changing gears, the necessary torque of the whole vehicle is provided by the motor. so that the running state of the vehicle can be maintained. However, the disadvantage of this arrangement is that the motor cannot be used to start the engine.

The engine control works stably in the range of high efficiency, low fuel consumption and low emission. The engine adopts a transmission system with high transmission efficiency, which directly drives the drive system, and there is no energy consumption caused by the series system in the process of energy conversion. Compared with the series structure, the parallel structure only needs two major power devices, the engine and the motor, and the two work together to meet the power requirements of the vehicle, so the choice of engine and motor power is more diverse than that of the traditional internal combustion engine vehicle. the selected power does not need to be too large.

The arrangement shown in Figure 3 is a series-parallel hybrid power system. The series-parallel hybrid electric vehicle combines series and parallel structural characteristics, consisting of engine, generator and drive motor. The generator is installed on the engine output shaft to ensure stable operation and power generation.

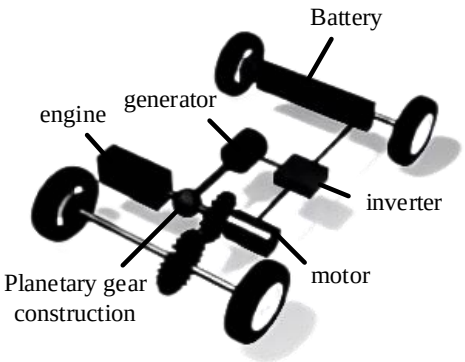


Figure 3. System diagram of series-parallel hybrid electric vehicle

The arrangement of hybrid power system is the combination of series and parallel. Part of the energy generated by the engine in this structure can be used to drive the generator to generate electricity to form a series structure; the other part can be combined with the motor to form a parallel

structure. Compared with the above two structures, the hybrid structure can adjust the power output of the engine more flexibly according to the driving conditions. The use of hybrid structure can make full use of the advantages of series structure and parallel structure, and avoid their disadvantages to the greatest extent, which is the most ideal layout structure for hybrid electric vehicles. but its disadvantages are complex structure, difficult research and high cost. Table 1 is a comparison of the characteristics of three hybrid electric vehicles with different connection modes.

Table 1. Comparison table of characteristics of different hybrid electric vehicles

Types of hybrid vehicles	Construction	Cost	Efficiency
Series hybrid electric vehicle	Complex	Cheap	Higher
Parallel hybrid electric vehicle	Simple	Cheap	Highest
Series-parallel hybrid electric vehicle	The most complex	expensive	Lower

3. Factors affecting brake energy recovery

When HEV braking decelerates and performs regenerative braking, the following three basic requirements should be followed [5] ：

(1) Tationarity: HEV is comfortable and smooth when braking.

(2) Safety: HEV cannot turn over, hold tight, or shake its tail when braking.

(3) Recover braking energy as much as possible: the biggest difference from traditional fuel vehicles is to maximize braking energy recovery on the premise of ensuring driving safety.

The main factors affecting the energy recovery of regenerative braking are as follows [6] ：

(1) The driving condition of the vehicle: due to the frequent traffic lights in the urban area, the braking times of electric vehicles are also increased accordingly, and the potential braking energy that can be recovered is also considerable. Electric vehicles are driving on the highway, as the opportunities for braking are relatively few, the energy recovery is also very limited.

(2) SOC (State of Charge, charged state) of the battery: the SOC of the battery limits the recovery and storage of energy, and overcharging will reduce the service life of the battery. There are also the charging efficiency and charging current of the battery.

(3) Motor: the greater the generating power of the motor, the greater the power generation efficiency, the more braking energy can be recovered.

(4) Electric vehicle transmission system: the higher the transmission efficiency of the transmission system, the more braking energy is recovered.

(5) Driving mode: if the driving mode is different, the stored renewable energy is also different.

(6) Braking force distribution control strategy: some focus on storing regenerated energy as much as possible, and some focus on braking performance optimization. The braking energy recovered is also different with different control strategies.

4. Regenerative braking Energy recovery system based on hydraulic system

4.1. Working principle of kinetic energy recovery of hydraulic system

The parallel hydraulic hybrid power system basically retains the traditional transmission structure. For hybrid electric, only one set of hydraulic system is attached to the hardware, and the transformation degree of the traditional automobile transmission system is not great [7]. The scheme is easy to refit, low cost, the system does not work full-time, the hydraulic pump / motor power requirements are small, and the hydraulic system failure will not cause the whole vehicle operation interruption, high reliability [8]. The sleeve system mainly includes torque couplers, hydraulic pumps / motors, high and low voltage accumulators and other devices, the structure of which is shown in Figure 4.

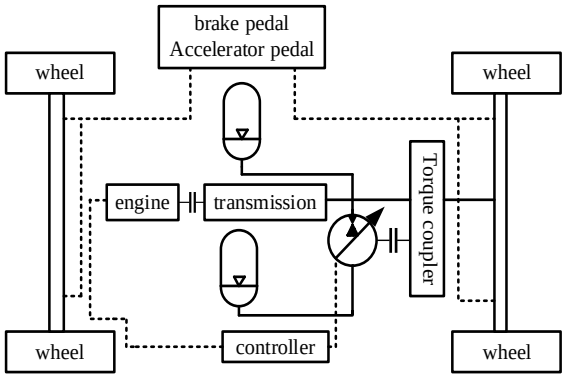


Figure 4. Parallel hydraulic hybrid system

Hydraulic hybrid power systems are mainly aimed at the deceleration braking, starting and acceleration process of the vehicle. In the process of vehicle braking, the hydraulic pump / motor acts as a hydraulic pump, and the rotating wheel drives the hydraulic pump to rotate through the transmission system. The hydraulic pump presses the low-pressure oil in the low-pressure accumulator into the high-pressure accumulator to compress the air bag volume of the high-pressure accumulator and convert kinetic energy into hydraulic energy to realize the recovery of braking energy. Hydraulic pumps / motors act as motors during vehicle start-up and acceleration. The pressure energy in the high pressure accumulator is converted into kinetic energy and the vehicle is driven by the transmission system.

Traditional hydraulic hybrid hydraulic systems consist of hydraulic pumps / motors, high pressure accumulators, low pressure accumulators, electromagnetic directional valves, relief valves and so on. Its structure is shown in figure 5.

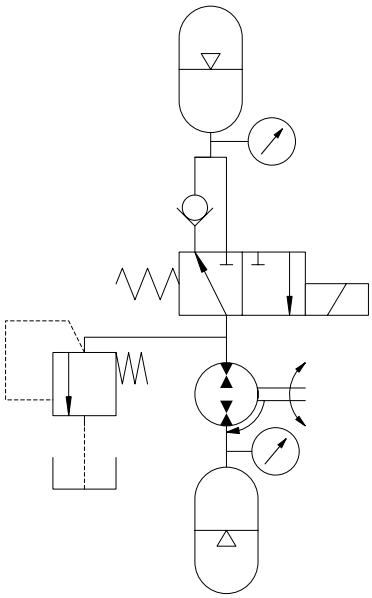


Figure 5. Hydraulic schematic diagram

Hydraulic system is mainly divided into two modes: drive and brake. In the drive mode, the hydraulic pump/motor plays the role of a motor, switch the reversing valve, release the high pressure oil in the high pressure accumulator, by the difference of pressure between the high and low pressure accumulator at both ends of the motor, drive the motor to rotate, and then drive the vehicle transmission system to drive the vehicle; In brake mode, have the effect of hydraulic pump, hydraulic pump/motor reversing valve switch, vehicle kinetic energy through the mechanical transmission system turns the hydraulic pump, hydraulic pump to low pressure accumulator of low pressure oil suction to the high pressure accumulator, oil squeeze the gasbag pressure potential energy, to realize the conversion of kinetic energy into hydraulic energy, kinetic energy recovery.

4.2. Practical Application

Continental Group MKC1 is already mass-produced integrated electro-hydraulic compound braking system MKC1. This system integrates the power motor, brake master cylinder and control system (ABS, ESC) to form a compact and light-weight integrated braking module.

This scheme has no vacuum booster and EVP, and no hydraulic pump or accumulator. Instead, it uses a high-performance motor to drive the piston in a straight line through a gear mechanism to generate brake master cylinder pressure. Compared with the ordinary braking system, it is lighter and faster in response. It can significantly improve the pressure building speed, effectively shorten the braking distance, and meet the higher requirements of the new advanced driving assistant system for the dynamic characteristics of braking pressure control. The function of coordinated regenerative braking is similar to that based on ESP/ESC and EHB technology, which can also achieve efficient braking energy recovery.

The brake pedal of the system can also be decoupled, there is no direct connection between the pressure building process and the brake pedal, and the pedal feeling is generated by a spring / buffer unit integrated in the execution module. The pedal feeling can be adjusted separately according to the requirements of the whole vehicle, and can also be adjusted separately according to different driving conditions (such as emergency braking) or operation mode (such as "movement"), without any additional measures, to achieve the perfect unity of regenerative braking and comfort. This scheme has been successfully applied to Nissan Leaf, Tesla Model S and Alfa Romeo Giulia models.

5. Regenerative braking Energy recovery system based on Flywheel

5.1. Principle of flywheel energy storage

Flywheel energy storage is a kind of energy device for the conversion between mechanical energy and electric energy, which uses physical methods to achieve energy storage results. In energy storage, the motor drives the flywheel to rotate, and the flywheel stores energy in the form of kinetic energy; when releasing energy, the flywheel rotates at high speed, drags the motor to generate electricity, and the kinetic energy is converted into electric energy [9]. As shown in Figure 6, the flywheel energy storage structure can be divided into rotor system, bearing system and energy conversion system [10].

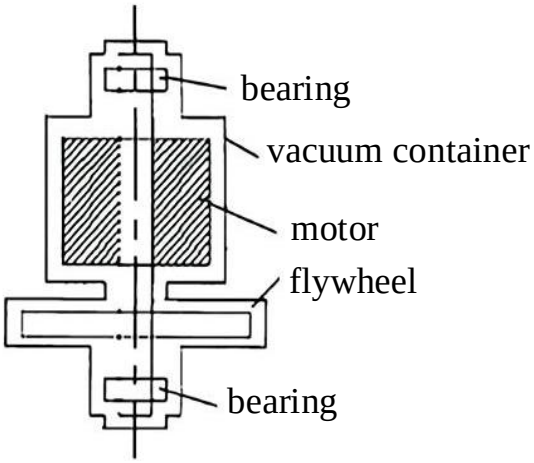


Figure 6. Energy storage structure diagram [10]

In a complete working cycle, the flywheel system can achieve three stages: power output, storage and release. At present, the flywheel energy storage system manufactured by technology is mostly composed of mass block and supporting mechanism. Among them, the magnetic bearing can eliminate the loss caused by friction, thus improving the service time of the flywheel. At the same time, the wind resistance will also cause the loss of the flywheel, so the application range of the flywheel energy storage system is small.

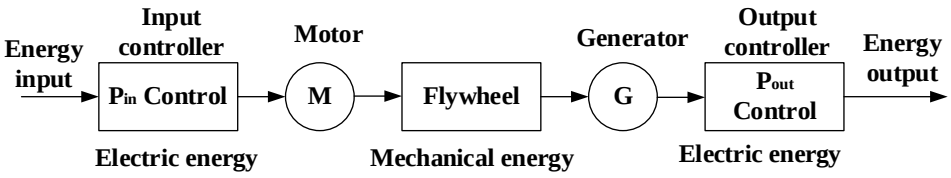


Figure 7. System structure drawing of flywheel hybrid

Figure 7 depicts the basic idea of flywheel energy storage. When storing energy, the motor-driven flywheel rotates at a high speed, converting electric energy into mechanical energy storage; when energy is required, the flywheel slows down, and the motor serves as a generator, converting the kinetic energy of the flywheel into electric energy output.; while idle operation requires very little loss. By controlling the speed up and down of the flywheel, the energy is stored and released.

5.2. Practical Application

For the application of mechanical flywheel energy storage system in vehicles, at present, the mechanical flywheel kinetic energy recovery system of VOLVO is the most mature and closest to mass production. In May 2021, the flywheel kinetic energy recovery system (FlywheelKERS) developed by Volvo Motor's powertrain division and SKF has been designed and a prototype has been manufactured.

In the mechanical flywheel kinetic energy recovery system, the flywheel module is connected to the differential of the automobile drive shaft through the semi-ring infinite transmission (IVT), clutch and three-stage gear transmission chain. In the flywheel module, the flywheel is contained in a vacuum shell, supported by specially designed bearings (even magnetic bearings), and the vacuum condition is maintained by a vacuum pump. The half-ring infinite transmission (IVT) is mainly composed of housing, input roller, output roller, power roller and hydraulic control module [11].

The kinetic energy from the body is stored in the flywheel module (in the form of flywheel rotation), and when it needs to be released, it transfers the energy to the rear axle to directly drive the wheel through the CVT transmission module. According to official test results, a four-cylinder turbocharged engine using this technology can reach the level of a six-cylinder turbocharged engine and reduce fuel consumption by 25% compared with a six-cylinder turbocharged engine. According to officials, Volvo has completed testing the system and is likely to carry it on the S60.

6. Regenerative braking Energy recovery system based on Super Capacitor

6.1. Supercapacitor energy storage principle

For an actual electric vehicle, the circuit of the energy feeder system is very complex. The circuit schematic is shown in figure 6.

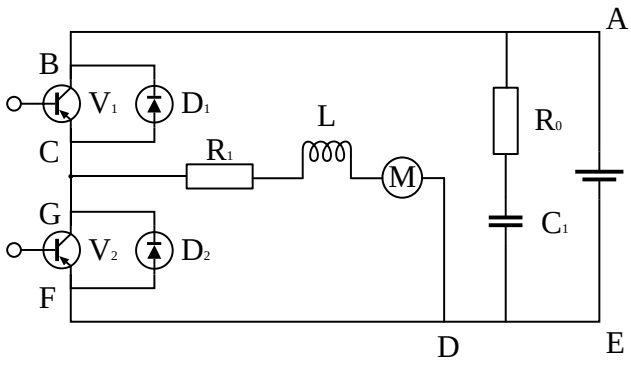
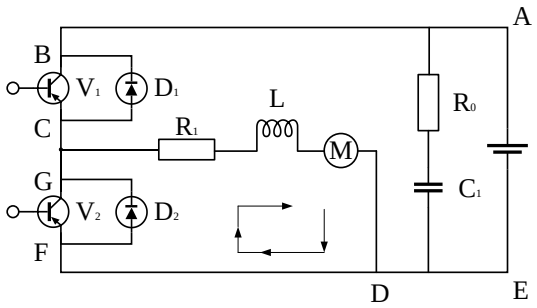


Figure 8. Principle of braking energy recovery system

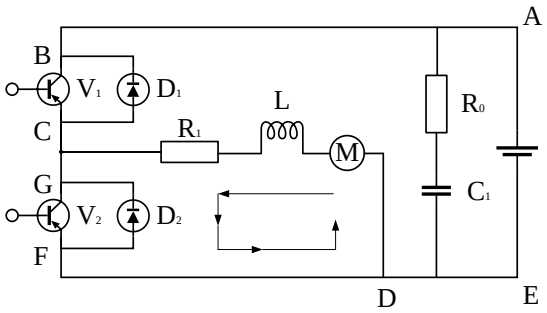
The circuit consists of two IGBT devices V1 and V2, resistor R, motor M, inductor L, etc. The function of S in Figure 8 is performed by the IGBT devices, and the control unit controls the turning

on and turning off of the IGBT. When the electric vehicle is running normally, V1 tube is on and V2 tube is off, and the working circuit is ABCDEA. When the driver needs to brake and relax the accelerator pedal, both V1 and V2 are off, and the current is lost through the CDFGC circuit, as shown in Figure 9(a). When the motor generates electricity, the battery current is reversed, at which time V1 is off and V2 is on, as shown in Figure 9(b). After Ton time, V2 tube is disconnected, as shown in Figure 9(c), and the power is backcharged to the battery.

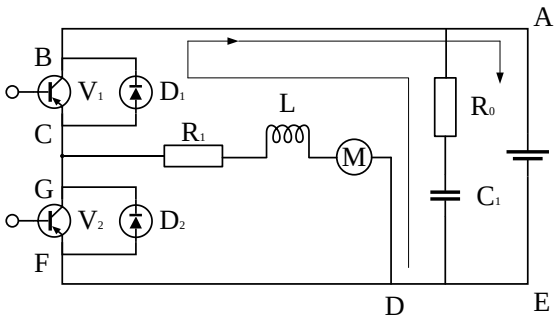
Supercapacitors are used as buffer devices for power converters. When a car is going downhill and braking, especially during emergency braking, a large amount of inertia energy is generated as part of the kinetic energy produced when the car is accelerating or decelerating. Usually, the energy generated is too large to be fully utilized in an instant because the drive motor power cannot be too large. Therefore, in the energy regenerative braking mode, the extra kinetic energy of the car is fed back from the wheels to the energy recovery device through the spindle of the drive motor and stored in the supercapacitor, which converts the mechanical energy of the vehicle into electrical energy and requires almost no additional charging of the supercapacitor during the entire operation of the car. According to calculations: regenerative braking can improve the range of electric vehicles by about 15%, so that hybrid electric vehicles can save fuel by about 40%, reduce pollution by nearly 80%, and realize the effective absorption and utilization of energy. The technology can also be applied to capacity buffering and recovery in elevators, high-speed rail, etc. [12].



(a) Braking energy recovery process when V_1 and V_2 disconnect



(b) Braking energy recovery process when V_1 disconnects and V_2 turns on



(c) Braking energy recovery process when V_1 turns on and V_2 disconnects

Figure 9. Braking energy recovery processes under different closing conditions. (a) V1 and V2 disconnect. (b) when V_1 disconnects and V_2 turns on. (c) V_1 turns on and V_2 disconnects

6.2. Practical application

Table 2. Comparison between different hybrid systems

Types of energy recovery device	Advantages	Disadvantages	Prospect
Hydraulic braking system based on vacuum assist	easy to implement; stability	low energy recovery rate; poor braking comfort	Optimize braking comfort
Hydraulic brake system based on ESP/ESC	carry out the coordination of feedback torque and hydraulic torque with high energy recovery rate	only applicable to small cars	
Hydraulic brake system based on EHB	Active boost function; dynamically control the coordinated distribution of motor feedback torque and hydraulic braking torque	high commissioning and maintenance costs; no weight advantage	appropriate simplification of the structure to reduce costs
Flywheel energy storage	high energy storage density and high power density	large equipment size; poor applicability	applications in the public transport industry
supercapacitor-based brake energy recovery device	fast charging speed; pollution-free	low specific energy but high specific power	develop new materials to enhance its energy density

At present, Beijing, Yantai and Shanghai have been experimenting with supercapacitor-powered buses in China. The supercapacitor bus produced independently by the domestic manufacturer Yantai Zhongshang can already reach a driving distance of 2km on a single charge, with a first charging time of 180S, an intermediate station charging time of 15 - 30s, a maximum driving speed of 60km/h, a maximum climbing degree of not less than 25, and good operation under braking conditions that can achieve energy regeneration back. Zhongshang Automobile has developed the third generation of supercapacitor vehicle, which has improved the range to 25km and the maximum driving speed of 70km/h [13].

A city hybrid bus is used as an example to show the actual situation of supercapacitor use in a vehicle. The city hybrid bus is powered by an 85KW asynchronous motor as the driving motor, fed by a 125KW diesel engine driving a synchronous generator at constant speed and an energy storage unit with a supercapacitor coupled to a power supply system coupled to a self-commutating bidirectional variator via a phase-controlled voltage regulator circuit chain. The supercapacitor starts to discharge when the vehicle speed is below 20km/h, and when the output power of the diesel engine is less than 50KW, the supercapacitor also starts to discharge. The supercapacitor can carry out energy recovery when the car is braking, and its energy storage unit and the diesel engine are in efficient operation. Through these advantages, ultracapacitors reduce fuel consumption by 26%, reduce the total energy demand of the city by 18%, and reduce air pollution within the city [14]. Ultracapacitors can be used not only in buses, but also in subways and cars that need to perform various acceleration and braking cycle.

7. Summary and Prospect

This paper analyzes the working principle and practical application of three different device based brake energy recovery devices as well as the market prospect, initially summarizes the advantages and defects of the current mainstream brake energy recovery devices on the market, and gives an outlook on their future market application prospect.

(1) Flywheel energy storage has the benefits of high energy storage density and high power density, and modern flywheel energy storage systems (FESS) bridge the gap between supercapacitors with low specific energy but high specific power and batteries with high specific energy but low specific power. Furthermore, FESS has a long cycle life, is not affected by temperature changes, has no performance degradation over time, and has a low environmental impact, making it one of the most promising short-time high-power energy storage technologies.

(2) The advantages of the vacuum-assisted hydraulic braking system are the use of most original brake system components, ease of implementation, mature technology, system stability, and cheaper cost. The downside is that the motor feed-back braking force is immediately overlaid on the original friction braking force, resulting in a low energy recovery rate, poor braking comfort, and no adjustment of the original friction braking force. Poor braking comfort is manifested not only in the impact and smoothness of motor feedback braking and friction braking coupling and switching, but also in the plateau area, where, due to low air pressure, EVP cannot provide the same high vacuum as in the plain area, the vacuum booster is under-assisted, and the pedal force increases. The hydraulic brake system based on ESP/ESC is smaller in size and lighter in weight than the conventional brake system, and it can coordinate feedback torque and hydraulic torque with a high energy recovery rate. However, the system's front axle is decoupled, the brake line is type II, rather than the standard X configuration, and the solution is only suited to tiny cars (full load vehicle weight not exceeding 1700kg). The hydraulic brake system's pedal decoupling based on EHB, pedal sense, can be designed flexibly, dynamically control the coordinated distribution of motor feedback torque and hydraulic braking torque, and prioritize the use of regenerative torque to achieve maximum braking energy recovery efficiency; at the same time, it has a powerful failure mode, ESP can compensate when ACM-H fails, and there is a mechanical structure to assure safety when hydraulic failure occurs. The system, on the other hand, has many parts, a complex structure, four additional brake pipes, little weight advantage, and substantial commissioning and maintenance costs.

(3) Because the supercapacitor-based brake energy recovery device relies on a double electric layer and a redox pseudo-capacitor charge to store electrical energy, the charging speed is very fast, only 10 seconds-10 minutes to reach more than 95 percent of the rated capacity, and it can be charged and discharged hundreds of thousands of times. In addition, the composition of raw materials, production, use, storage and dismantling process are pollution-free, so super capacitor is an ideal green power source. Today, the country advocates the construction of "two types" society and the development of green energy-saving and environmental protection industry, and the industrialization and application of the corresponding scientific research results are taking advantage of the natural time. However, super capacitor is more as a supplement of power battery: it can greatly improve the peak output capacity of the system with a small increase in cost, or reduce the frequency of high current discharge of power battery for a short time. It is only adopted in some buses, but not industrialized in the whole auto industry, especially in passenger cars; besides, compared with batteries, energy density is not the strength of supercapacitors, and the industrialization of many new technologies, such as the application of graphene and other new materials to improve their energy density, is still pending. At present, the joint use of ultracapacitors and batteries in new energy vehicles to improve the power performance and cycle life of batteries alone is being favored by the industry. Moreover, the joint application of two energy storage devices will definitely bring more complex control system, which is a big test for the overall stability of the vehicle system.

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