Research and analysis on brake energy recovery of pure electric vehicles

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Abstract. Environmental pollution and other problems are becoming increasingly serious with the energy crisis. Pure electric vehicles, as a new green and pollution-free means of transportation, are increasingly favoured by the public. Compared with traditional fuel vehicles, pure electric vehicles have a shorter range, and brake energy loss accounts for approximately 10-30% of the total energy consumption. Brake energy recovery technology can effectively improve the energy utilization rate of pure electric vehicles and increase their range. This article focuses on studying different methods of braking energy recovery for electric vehicles, using comparative analysis and selecting several sets of schemes with higher recovery efficiency for analysis, pointing out the advantages and disadvantages of different methods. Research indicates that electrochemical energy storage represents a superior approach for recycling energy due to its ability to enhance energy recovery efficiency through algorithmic optimization of motor braking force distribution. However, the application of mechanical energy storage and hydraulic energy storage in pure electric vehicles necessitates further improvements to address various technical challenges.

1 Introduction

Amidst mounting concerns over the energy crisis and escalating environmental pollution, pure electric vehicles have gained substantial public favor as a novel, eco-friendly mode of transportation devoid of pollution. Pure electric vehicles have a shorter range than conventional fuel-powered vehicles, and brake energy loss contributes to 10–30% of the total energy consumed. Braking energy recovery technology can effectively increase the energy utilization rate of pure electric vehicles and extend their range. The selection of energy storage methods has a significant impact on the efficiency of the braking energy recovery system. So this article focuses on studying and comparing different methods of braking energy recovery for electric vehicles and selects several sets of schemes with higher recovery efficiency. The brake energy recovery system's basic operation is to transform a portion of the kinetic energy into another type of energy during the braking phase and then store it in the energy storage device using a variety of techniques. According to various energy recovery techniques, the stored energy can be separated into mechanical energy storage, hydraulic energy storage, and electrochemical energy storage. The stored energy can then be transformed back into kinetic energy through the driving device. Presently, domestic and international energy storage systems for braking energy recovery have been extensively studied, and several achievements have been achieved in the study and strategy research. This paper summarizes domestic and foreign literature research on different forms of energy storage, reviews the current state of study and the achievements of the above studies and makes a comparison of actual applications, and proposes the future development of the storage system for energy recovery.

2 Mechanical energy storage

Nowadays, flywheel storage and spring storage are the two most popular types of mechanical energy storage. The utilization of flywheel storage is common in industries like transportation and aircraft. The idea behind flywheel energy storage is to add a flywheel to a vehicle to enhance its overall mass. The vehicle body's inertia performance is turned into flywheel kinetic energy upon braking. In order to achieve the goal of recovering braking energy, the flywheel's stored kinetic energy is transformed into driving kinetic energy through the transmission mechanism when the automobile resumes (Figures 1 and 2).

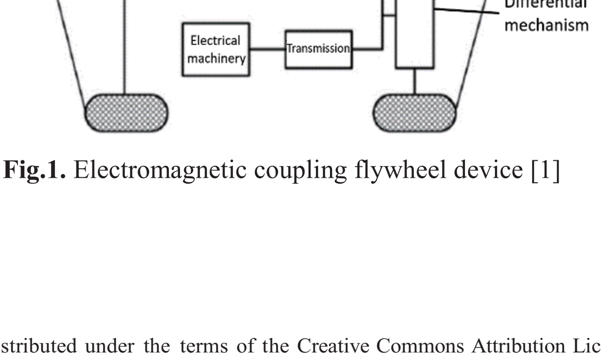

Fig.1. Electromagnetic coupling flywheel device [1]

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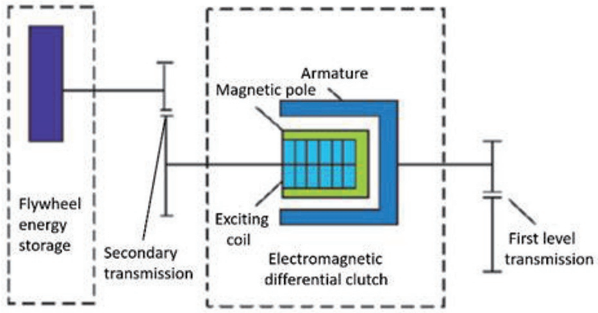

Fig.2. Car chassis layout [1]

An electromagnetically coupled energy storage flywheel was designed by Li Chunlei et al. [1]. The device uses the electromagnetic differential clutch as a transmission system so that the magnetic torque can transmit mechanical energy to the flywheel storage. According to the calculation formula given in the literature$\eta=100\times\Delta Et/\Delta E$ (ΔE is the changes in external output energy, is energy variation of energy storage flywheel before and after braking). The energy recovery efficiency of the energy storage flywheel can be obtained. It was found that the higher the initial braking speed, the more energy the flywheel can recover, and the recovery efficiency is not less than 22.4%. The advantage of this method is its simple structure and high energy density. The disadvantage is that it cannot provide power stably for a long time due to friction. Porsche's 918 concept car currently adopts a similar flywheel energy storage system in practical use, which can provide an additional 2×75 kW of additional power.

Vortex spring energy storage is a technology that utilizes elastic potential energy for energy storage. The working principle of vortex spring energy storage is to fix one end and apply torque to the other end. Under torque, the spring undergoes curling and elastic deformation. When the car restarts, the ability to release the elastic potential of the vortex spring converts it into kinetic energy for the car to recover braking energy.

A Vortex spring braking energy recovery was designed by Shan Wenze (Figure 3), which is added to the vehicle's original structure through parallel connection, and the device mainly includes a transmission control structure, a drive control structure, and a vortex spring energy storage unit. When the device starts operating, the torque of the driving wheel shaft is transmitted to the vortex spring shaft, and the device begins to store energy [2]. When the braking process is completed, the gear stops meshing, and the pawl is stuck on the ratchet, preventing the vortex spring shaft from reversing and completing the braking energy recovery. According to the model experiment of Simulink in the literature, the braking energy recovery efficiency using planar vortex spring coil springs can reach over 60%. Compared to flywheel energy storage, the energy recovery efficiency of vortex spring energy storage is much higher [2]. However, the device is still in the simulation model stage and has not simulated the complete road conditions. So there is currently no practical application model for the device.

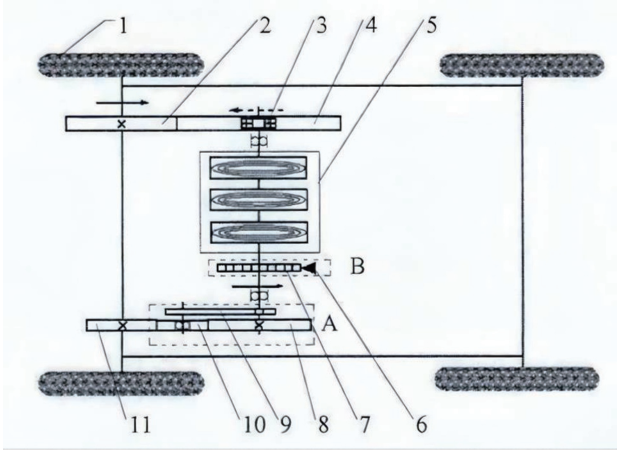

Fig.3. Working principle diagram of braking energy recovery [2]. 1-Driving wheels;2-Output gear a;3-Unidirectional bearing;4- Output gear b;5- Spring energy storage unit;6- Pawl;7- Ratchet wheel;8- Outer gear;9-Rocker arm;10- Idler;11- Input Gear

3 Hydraulic energy storage

Hydraulic brake energy recovery system refers to the energy recovery system that uses hydraulic energy storage as the main energy storage component. It uses a hydraulic variable pump/motor with reverse action to recover and release vehicle braking energy. Since the efficiency of a hydraulic energy recovery system is higher than that of an electric energy recovery system [3], more energy can be recovered and released at the same time under the same conditions, which improves the driving range of the vehicles. Besides, the use of hydraulic energy recovery has little change to the automobile power transmission system, which is relatively simple and more reliable than the control link of the electric energy recovery system. At present, there are different forms of hydraulic energy-saving vehicles researched and developed abroad, which can be mainly divided into different forms according to their power transmission system configuration and combination methods, for example： 1.The typical representative of the series structure form is the full hydraulic hybrid system of the US EPA [4]. It has a simple structure and is easy to control different parameters of the system；2. Parallel construction, such as the Cumulo drive system of the Swedish company Volvo [5], has high energy efficiency and little modification to the car. Hybrid structure form, such as the constant pressure source (CPS) hydraulic drive system developed in Japan in the 90s of last century, has a good energy-saving effect and simple structure.

Zhou Lingxiao and others focused on the CPS system and proposed the regenerative braking hydraulic system scheme (ECPS) for electric vehicles. It is connected in parallel with the power system and determined that the transmission system scheme was a rear-mounted parallel drive system. The ECPS system structure is shown in Figure 4.

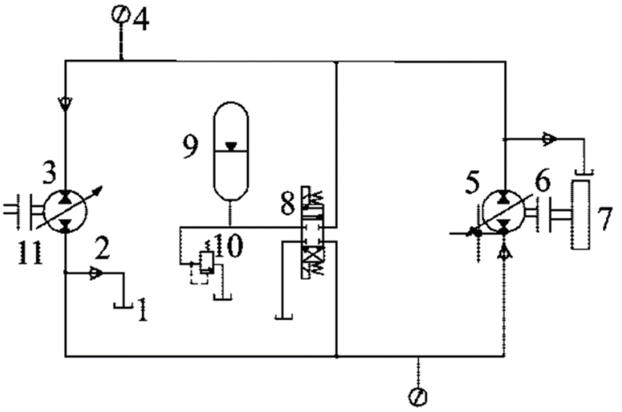

Fig.4. ESPS hydraulic system structure [6]
1—Fuel tank；2—Check valve；3—Displacement pump/motor connected to the transaxle；4—Manometer；5—Displacement pump/motor connected to the flywheel；6—Clutch；7—Flywheel；8—3/4-way directional valve；9—Accumulator；10—Relief valves；11—Total clutch

It is found that the larger the displacement of the hydraulic pump/motor, the more energy that is saved. However, as shown in Table 1, when the pump/motor displacement exceeds a particular value, the energy recovery effectiveness of the hydraulic brake energy recovery system would decline as a result of the increased resistance on the pump/motor. According to the findings, ECPS electro-hydraulic hybrid vehicles' driving range is increased by roughly 25% when compared to electric vehicles without ECPS. The battery's depth of discharge reduces as the load on the motor lowers, extending the battery's lifespan.

A hydraulic energy storage braking energy regeneration device for electric vehicles was created by Ding Zuowu and others with separate intellectual property rights [7]. The system utilizes the hydraulic energy storage braking energy regeneration system to recover braking energy when the vehicle brakes to prevent the waste of braking energy; During the vehicle acceleration stage, the stored hydraulic energy is used to drive the vehicle to reach a certain speed before starting the motor, to avoid the impact of high current consumption on the cycle life of the lithium-ion battery pack when the motor is running at low speed, and to increase the efficiency of the system. Additionally, he established the hydraulic energy storage braking energy regeneration system parameter model for electric vehicles, checked the accuracy of the model, and proposed the braking control strategy of the vehicle braking process of the hydraulic energy storage braking energy regeneration system under various operating conditions. He separated the four working situations of the hydraulic energy storage brake energy regeneration system's vehicle braking process into four categories: coasting, medium intensity, emergency, and gradual deceleration braking. For various braking conditions, the pertinent force distribution and control methods were investigated.

Table 1 The energy recovery efficiency of hydraulic regenerative braking system [6]

No.	Hydraulic pump / motor displacement / L	Initial kinetic energy of the car/J	Flywheel final speed/($r\cdot min^{-1}$)	Flywheel energy storage size/J	Energy utilization of ECPS system/(%)
1	75	167580	1200	39844	23.8
2	85	167580	1410	55134	32.9
3	95	167580	1550	66529	39.7
4	105	167580	1795	89320	53.3
5	115	167580	1910	101050	60.3
6	125	167580	2130	125685	75.0
7	135	167580	1790	88817	53.0
8	145	167580	1460	78763	47.0

4 Electrochemical energy storage

Electrochemical energy storage is widely used in the braking energy recovery system of pure electric vehicles today. The principle of electrochemical energy storage is to use the external characteristics of the motor. When the car brakes, the motor operates in generator mode. The rotating wheels drive the motor rotor to rotate through the transmission system, and the motor converts kinetic energy into electrical energy and stores it in the form of electrical energy in the automotive chemical battery. When the car needs drive energy, the electric motor is used to convert electrical energy into kinetic energy output. Due to the current limitation of charging and discharging power of pure electric vehicle power batteries and the limitations of external characteristics and maximum power [8], the current research direction of electrochemical energy storage is mainly divided into two aspects: rational distribution of electric machines power and improvement of charging power (Figure 5).

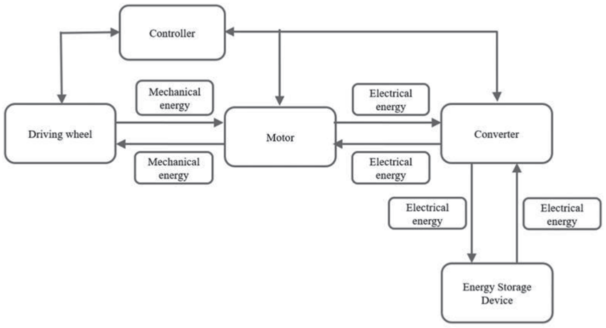

Fig.5. Principle diagram of electrochemical energy storage (picture/image credit: original)

Reasonable distribution of braking force of the motor is to distribute the ratio of the braking force of the motor and hydraulic braking force through the control algorithm, to meet the total braking force needs of each stage in the braking process to maximize the energy recovered by the motor . Xu Wei et al. studied a braking energy recovery scheme for a four-wheel hub motor [9]. This study builds a battery life model and a power consumption model on how to achieve a balance between the two. The article also designs a coordinating controller for motor braking and hydraulic braking. After the simulation analysis through simulink, it is found that the scheme can reduce the battery life loss to different degrees under different weight settings for energy recovery and battery life (Figure 6).

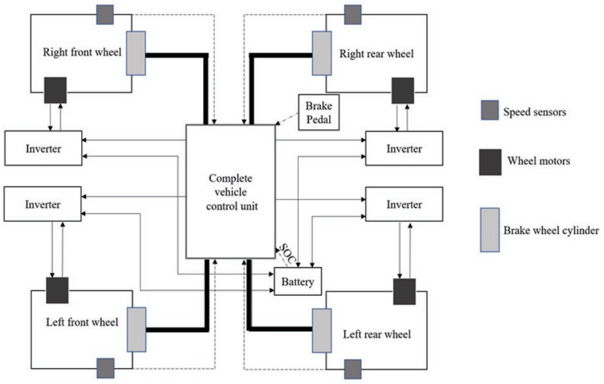

Fig.6. Four-wheel hub motor braking schematic (picture/image credit: original)

Zhu and coworkers of BYD Auto invented and applied for a patent for a new energy recovery control strategy. The research designed a system to control the energy recovery torque based on the driving habit factor [10]. The method recognizes the driver's driving habits and changes the feedback torque in real time to recover more energy and thus extend the range.

In the direction of increasing the charging power, Sun et al. from Hefei University of Technology used film capacitors as auxiliary energy storage devices to increase the braking energy recovery capacity of electrochemical energy storage devices [11]. Compared with supercapacitors, film capacitors have the advantages of the large operating voltage of a single unit, no charge/discharge equalization control, and a simple structure. In this study, simulations under cyclic conditions and road performance tests of the prototype system of film capacitors were conducted. The results show that the film capacitor can be charged and discharged with high current, significantly enhancing energy recovery efficiency and electric vehicle dynamics. The feature of a no charge/discharge equalization control circuit makes the film capacitor simpler in structure and lower cost than the supercapacitor.

5 Conclusion

In order to increase the battery-electric energy utilization rate, the cruising range of electric vehicles, and the competitiveness of pure electric vehicles in the automotive market, it is crucial to conduct research on the regenerative energy system of pure electric vehicles. Mechanical energy storage systems, hydraulic energy storage systems, and electrochemical energy storage systems are the three primary categories of pure electric car energy recovery systems. From our investigation, the following conclusions have been made:

1. The hydraulic energy storage system is generally used in large vehicles for its low energy density and efficiency;
2. The flywheel is generally used for buses with frequent starting conditions because of its poor long-term energy storage ability;
3. The energy recovery efficiency of the electrochemical energy storage system can be continuously optimized and improved due to the size of the motor regeneration braking force can be programmed to achieve different braking energy recovery strategies.
4. Theoretically, the recovery efficiency of hydraulic and mechanical energy storage is higher than that of electrochemical energy storage. But electrochemical energy storage is currently the best approach for it can better meet the needs of the actual market and is widely used in civil electric vehicles.

In the future development of flywheel energy storage, it is still necessary to address the large flywheel mass during vehicle steering, which can cause a certain eccentricity when rotating the flywheel, affecting driving safety. The current research directions include strengthening chassis structures and reducing effects through resonance. Further, subsequent actual model testing is required to provide a more precise simulation of the vortex spring energy storage. Hydraulic energy storage devices are not suitable for loading on small cars due to their large size and expensive materials. To solve this problem, it is necessary to simplify the hydraulic energy storage device and save costs and space as much as possible. Finally, electrochemical energy storage is feasible as the distribution of motor braking force can be optimized through algorithms. Further research should focus on improving the efficiency of algorithms and researching new pure electric vehicle batteries to optimize the efficiency of recycling and charging.

Acknowledgment

Authors contribution: All the authors contributed equally and their names were listed in alphabetical order.

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