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Comparison of Hybrid Powertrain Systems and Automotive Battery Technologies: Performance Metrics, Applications, and Trade-offs

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Abstracts:

This paper first compares series, parallel, and power-split hybrid systems. Then, it analyses Nickel Metal Hydride Battery, Lithium Iron Phosphate Battery, and Lithium Manganate battery by testing their efficiency, application scenarios, and safety. The investigation shows that the performances of different power systems are decided by both designed structures and different battery types. That means the reasonable matching of power system and battery can improve the total efficiency of the vehicle. Also, the new energy market in the future will continually shows a development trend of coexistence of multiple technologies because it is difficult for a single technology to completely replace others. In addition, the research investigates the impact on key parameters including fuel intake and charge behaviors, hence providing an overall framework for evaluating their overall impact on automobile efficiency and commercial viability. In the end, it also points out the importance in considering real-world driving cycles in order to effectively analyze their relationships, which can consequently make the results compatible with the needs for real-world applications.

Keywords: Hybrid system; new energy; battery.

1. Introduction

Nowadays, due to the increasing public awareness of environmental protection, the demand of sustainable transportation has accelerated new energy car's development. As a bridge between traditional single-fuel car and pure electric car, hybrid car and hybrid systems have improved a lot in order to balance each working situation and try to find a best way to increase efficiency, deal with rising fuel costs, and face the strict regulation of emissions (e.g., EU 6d, China's GB 18352.6). At the same time, batteries, one of the most important parts of new energy car, have experienced a great change, too. Different technologies and different kinds of batteries impact the design of vehicles and influence their performances. However, the intricate interaction between powertrain architectures and battery technologies remains unknown, so we need a systematic comparison of their advantages and drawbacks. Hybrid systems can be divided to three different kinds: Parallel hybrid system, Series hybrid system, and Power-split hybrid system. All of them have different best-fit working situation, which means if they are putted to an unsuitable place to use, they will even cause a high fuel cost than conventional vehicles. Regardless of differences in their power coupling and energy transfer methodologies, the common goal is always the same: to improve fuel efficiency and lower emissions by combining their thermal-electric power systems. Concurrently, batteries have developed to many types, such as Nickel Metal Hydride Battery, Lithium Iron Phosphate Battery, Lithium Manganate battery, and so on. All of them have different traits, so they fit different types of new energy cars.

Now the investigations always focus on hybrid systems or batteries independently, sometimes, they neglected the importance of combining the two parts together to find a connection. For example, Song discussed about different hybrid systems but omitted battery technology impacts on range and charging dynamics [1]. Similarly, JB Goodenough analysis of batteries emphasized energy density improvements without addressing how these gains translate to powertrain design trade-offs in real-world driving cycles [2]. This can show us the importance of making a system includes many sections, such as energy efficiency, power density, and application scenarios.

This study's purpose is to fill this gap by analyzing different hybrid systems and battery kinds. It will include:

(1) introduce different kind of hybrid systems and battery types.

(2) Identify optimal powertrain-battery combinations for different types of vehicles

(3) provide an entire perspective for automakers.

2. Hybrid Systems

Hybrid electric vehicle (HEV) powertrain systems are fundamentally categorized into three types: series, parallel, and power-split configurations [3].

2.1 Series Hybrid System

2.1.1 The structure of the series hybrid system

Fig. 1 has showed the basic circuit structure of the series hybrid system. Its basic operating principle is that the engine can charge the battery when there's no enough energy storing in it. The engine can't be used to drive the vehicle whenever. working Before departure, the battery will be charged via a charging station. If the battery charge is lower than a certain level, the Series hybrid system will start the engine to generate electricity by driving generator. Then the electricity can be stored in the battery. Likewise, when charging is over, the engine can shutdown automatically. The vehicle was driven solely by using the motor. To be specific, this kind of system can be seen as a pure electric car with a fuel-based portable charger [4].

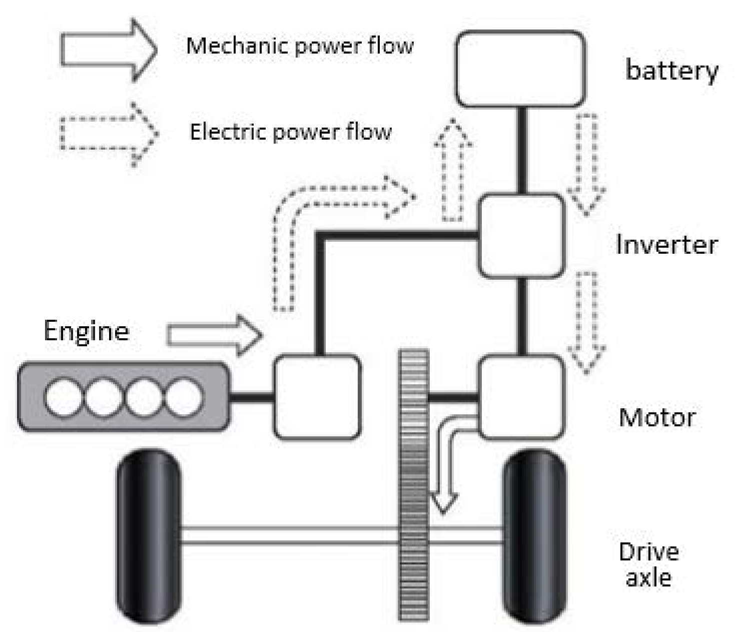

Fig. 1 Series Hybrid system [4].

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2.1.2 Features

This system can make sure that the engine is always working at the best range with almost highest fuel efficiency. Besides, when the vehicle is passing some important buildings, such as school, the driver can close its engine to decrease the noise. This kind of system is easy to fix because of the basic composition. However, this kind of vehicle needs a motor with high power because it's the only power source of propulsion system. Also, there's no gear box to let the motor fit high speed running. So, it will cause a low fuel efficiency. What's more, the energy loss during the transmission between engine and generator is large [5-7].

2.2 Parallel Hybrid System

2.2.1 The structure of the parallel hybrid system

Fig. 2 has showed the basic circuit structure of the parallel hybrid system, which includes at least a high torque motor, an engine, and a Power Coupler. Both engine and motor can be used to drive the vehicle. The battery should be charged via a charging station before departure. They can work together or individually and won't influence other. To be more specific, when the vehicle needs to accelerate rapidly (when the driver Press the accelerator hard), both engine and motor will drive the vehicle simultaneously. When the vehicle is stopping, the engine can shutdown automatically; only the motor will be used to start the vehicle to move. When the vehicle is driving on highways, only motor will be used because this kind of vehicle always have an AMT gearbox to make sure the engine can stay in the best efficiency range in different working situations. Apart from automatic power source switching, the driver can choose to stop the engine or the motor by their judgements of roads. [8, 9]

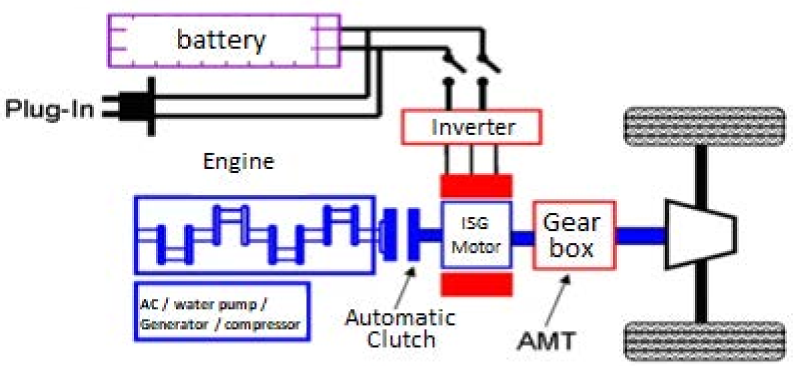

Fig. 2 Power-split hybrid system.

2.2.2 Features

This system can avoid engine working in low efficiency range and only use motor to drive, such as during the congestion. This can reduce a lot of emission caused by incomplete combustion. Besides, because engine and motor can work separately, when something went wrong on one of the driving systems, the vehicle can still work by using the other part. It has the similar structure to conventional vehicles, so there're less things to learn for drivers and maintenance staff. On the other hand, this kind of vehicle can't make sure that the engine can always work in the most efficient way, so the gas emission is higher than series systems. Also, the gear box of the system makes the shifting smoothness of this vehicle poor and caused a bad experience of driving of taking the vehicle [10-12].

2.3 Power-split Hybrid System

2.3.1 The structure of the power-split hybrid system

Fig. 3 has showed the basic circuit structure of the power-split hybrid system, which is the most complicated hybrid system among the three. It includes a high torque motor, an engine, and automatic clutch, generator. The working situations can be totally divided to three different kinds:

(1) The vehicle is slower than the critical speed. At this time, the clutch will disengage the connection between engine and motor, so the engine will be only used to drive the generator and charge the battery. Only the motor is used to drive the vehicle.

(2) The vehicle is faster than the critical speed. At this time, the clutch will connect the motor and engine together. The engine will work smoothly and let the vehicle stay at constant speed. When the vehicle needs to accelerate, the motor will provide additional power.

(3) The vehicle is slowing down. When the vehicle is slowing down, the clutch will disconnect the engine and the motor. The drive axle will drive the motor to generate electricity and charge the battery. This process is also known as KERS and widely used in pure electric cars.

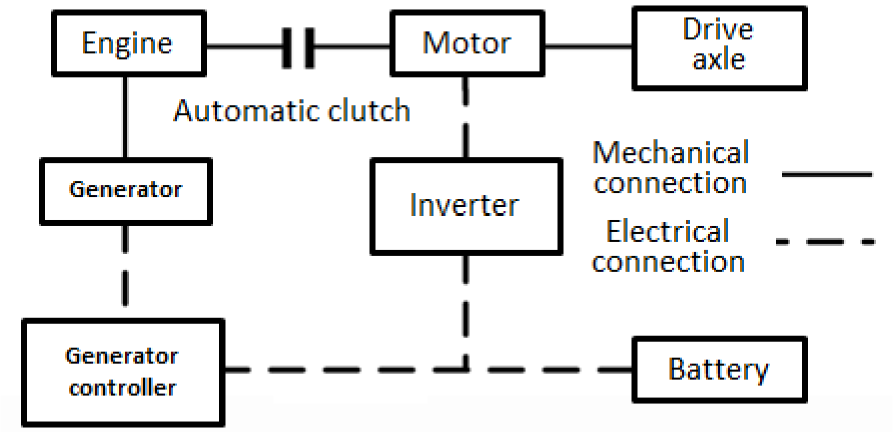

Fig. 3 Power-split hybrid system [13].

2.3.2 Features

This system provides advantages of both series hybrid system and parallel hybrid system because it can decide to use series hybrid mode or parallel hybrid mode. Therefore, the car can choose a mode automatically. As a result, it can fit each working situations and can keep a high fuel efficiency. What's more, because there's no gear box between the motor and drive axle, it will be smoother when the car is accelerating. But this kind of system is difficult to fix because of its complexity. The maintenance workers need to be trained a lot before getting the job. Also, the high complexity makes the vehicle become more vulnerable, which means there might be more unscheduled maintenance and decreases the utilization rate. Also, because the system needs battery to drive, the vehicles weight increases a lot and adds costs to manufacture [14-17].

2.4 Future Expectations

In the future, due to the increasing energy density in batteries, cars will be replaced by pure electric cars except for fuel cell vehicles such as Hydrogen Fuel Cell Buses, which use this kind of system [18]. This system will continue to develop and exist due to its easy maintenance and fitness for different working situations, such as low speed in the city and high speed on highways, and it will become one of the dominant systems and not disappear until the energy density of batteries can be increased to a level that allows electric cars' endurance to match that of traditional cars. The power-split hybrid power system integrates the merits of the above two systems, thus having a high capacity to adjust to varying operating conditions, both low-speed and high-speed. It has also given rise to numerous variations, e.g., the planetary gear hybrid power system, etc., and with advancing technology in the years to come, it has the potential to take the place of the current series and parallel hybrid vehicles.

3. Batteries

Nowadays, many scientists focus on finding a kind of battery which can balance energy density, safety, charge-discharge cycles, and charging speeds. The article is going to introduce three kinds of different batteries that are widely used in new energy cars. They have showed about different kinds of batteries' advantages and drawbacks during their investigations.

3.1 Nickel Metal Hydride Battery

3.1.1 Components and working principle

The main components of a nickel-metal hydride power battery are as follows:

The positive electrode is made of nickel hydroxide attached to a foam nickel substrate; The negative electrode is composed of rare earth-based hydrogen storage alloy powder with a steel strip as the substrate. There is a separator between the positive and negative electrodes, which is generally made of nylon, or specially treated polyethylene or polypropylene. The battery also contains an electrolyte, which is a strong alkaline solution. It may be one of potassium hydroxide, lithium hydroxide, or sodium hydroxide, or a mixture of these in a certain proportion [19].

When the battery is discharging, the positive electrode Nickel oxyhydroxide is reduced to Nickel hydroxide, and the negative electrode hydrogen storage metal is oxidized to metal. When the battery is charging, the positive electrode Nickel hydroxide is oxidized to Nickel oxyhydroxide, and the negative electrode metal is reduced to hydrogen storage metal [20].

3.1.2 Features

The Nickel Metal Hydride Battery has been putted into use for more than 20 years, which means the companies have a relatively mature techniques to make it. As a result,

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the price of Nickel Metal Hydride Battery can be cheaper. What's more, this kind of Battery has a stable chemical property, so the risk of explosion or fire during overcharging or over-discharging is lower, which makes it safer to use. Also, due to the chemical components don't have any toxic material in it, the battery is also environmentally friendly. However, the Nickel Metal Hydride Battery has a lower energy density than other kinds of batteries such as lithium-ion batteries, which means the car need to carry a heavier battery series for the same capacity. Also, due to the strong alkaline solution in the battery, if the battery casing is damaged, the electrolyte leakage may corrode equipment or cause skin burns during repairing. Lastly, Nickel Metal Hydride Battery has a higher self-discharge rate, which means the car will lose charge quickly when idle. Thus, recharging is often needed after a long period of inactivity [21].

3.2 . Lithium Iron Phosphate Battery

3.2.1 Components and working principle

The major cathode material used in lithium iron phosphate batteries is lithium iron phosphate, usually prepared through carbothermal reduction. At the same time, other dopants such as magnesium, titanium, and chromium are often used to enhance the performance. The anode material mostly consists of graphite, due to its layered structure that ensures the effective intercalation of lithium ions, as well as its very high electrical conductivity. In addition, both graphitizable carbon and non-graphitizable carbon may be used as efficient materials for anodes in battery applications.

When the battery is discharging, the positive electrode Lithium iron phosphate is reduced to Iron phosphate, and the negative electrode Graphite (intercalated with lithium) is oxidized to Graphite. When the battery is charging, the positive electrode Iron phosphate is oxidized to Lithium iron phosphate, and the negative electrode Graphite is reduced to Graphite intercalated with lithium [22].

3.2.2 Features

First, from a safety perspective, the main structure of lithium iron phosphate material is PO_4, and its bond energy is much higher than that of the M-O bond in the MO_6 octahedron of ternary materials. The thermal decomposition temperature of the lithium iron phosphate material in the fully charged state is approximately 700°C and makes it safer. Second, after material modifications, lithium iron phosphate batteries can achieve relatively high charge-discharge rates, meeting medium to high power requirements. Lastly, lithium iron phosphate batteries generally have a cycle life of more than 2000 times, and their structural stability is strong, making them suitable for scenarios that require long-term repeated charging and discharging. However, due to its chemical properties, the energy density of the lithium iron phosphate batteries is lower than that of ternary lithium batteries. Also, it can't work well in alpine regions because the low temperature will decrease the ionic conductivity of lithium iron phosphate, which leads to a batteries' capacity degradation and a longer charging time [23, 24].

3.3 Lithium Manganate Battery

3.3.1 Components and working principle

The cathode material of lithium manganate batteries is spinel-type $LiMn_2O_4$. During preparation, it is mixed with conductive agents, binders and solvents in proportion, then coated on aluminum foil, and made into cathode sheets through drying, rolling and cutting processes. The anode material is mainly low-cost natural graphite. For preparation, the anode active material is mixed with related auxiliary materials, coated on copper foil, and made into anode sheets through the same subsequent processes. In addition, hard carbon, soft carbon, etc. can also be used as anode materials. Hard carbon has better cycle performance due to its interlayer spacing characteristics, but there were no mature products in China at that time [25-28].

When the battery is discharging, the positive electrode Lithium manganese oxide is reduced to Lithium manganese oxide, and the negative electrode Lithium-intercalated graphite is oxidized to Graphite. When the battery is charging, the positive electrode Lithium manganese oxide is oxidized to Lithium manganese oxide, and the negative electrode Graphite is reduced to Lithium-intercalated graphite.

3.3.2 Features

The lithium manganate batteries have a high charging speed because of its intrinsic three-dimensional lithium-ion diffusion channels, which facilitate rapid ion transport during high-rate charge and discharge processes. Also, Lithium manganate batteries can instantly increase power output because they have a high ion diffusion rate. After improvement of the electrolyte, they can still release 99% of their capacity under 5C high-rate discharge. What's more, the lithium manganate batteries exhibit slower attenuation under shallow cycle conditions due to the relatively stable lattice structure. They can have a cycle life of more than 1000 times. However, the manganate batteries will experience a deterioration when working at a relative high temperature. Also, the energy density of them is not as high as that of ternary lithium batteries.

Lastly, during the charging and discharging process of spinel lithium manganate, especially in deep cycles, Mn^{3+} is prone to Jahn-Teller distortion. It leads to the destruction of the lattice structure. At the same time, manganese ions are easily dissolved into the electrolyte, resulting in the loss of active substances, making the battery capacity gradually decrease with the increase of cycle times [26-28].

3.4 Future Expectations

Due to the escalating endurance requirements and the rapid advancements of other battery types, the Nickel Metal Hydride Battery is nearly being supplanted by lithium-ion batteries. Although lithium iron phosphate batteries have certain drawbacks, they can still be well-suited for the working scenarios of series hybrid systems and power-split hybrid systems. The engine can supplement power at any time, which diminishes the significance of energy density. Moreover, the inherent safety of this battery makes it less risky to be arranged alongside the engine and fuel tank. On the other hand, lithium manganate batteries can fit the working situations of both parallel hybrid systems and power-split hybrid systems. These systems do not demand a high endurance in pure electric mode, so the battery will not be used continuously for a long time, which can prevent high temperatures and deep cycles. Additionally, the high charging speed can reduce the operating time of the engine, resulting in lower emissions.

4. Conclusion

As national policies continue to promote the new energy development, the role of energy storage systems becomes more and more important. This paper highlights the differences, such as efficiency, operating conditions, and safety, between various techniques by comparing and analyzing hybrid systems (series hybrid system, parallel hybrid system, and power-split hybrid system) and main types of batteries (Nickel Metal Hydride Battery, Lithium Manganate battery, Lithium Iron Phosphate Battery). The investigation reveals that the performance of a hybrid system not only depends on the structure, but also has a close relationship with the type of battery being chosen. In certain situations, proper matching of hybrid systems and battery types can improve overall performance and economy.

Although different types of batteries exhibit varying performances in practical applications, the new energy market will still present a pattern of technological diversification and parallel development in the future. Both the favor toward Lithium Iron Phosphate Battery in the commercial vehicle market and energy storage fields due to its stability, and the wide use of lithium manganate batteries in some hybrid vehicle models due to their fast-charging advantages, demonstrate that no single technical route will completely replace others in the short term. In the future, researchers should focus on the collaborative matching of power systems and batteries in order to promote more rapid development of new energy technologies.

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