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Research on Key Technologies and Comprehensive Management Strategy of New Energy Hybrid Electric Vehicles

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Abstract

New energy hybrid electric vehicles (HEVs) have emerged as a promising technology for reducing the usage of fossil fuels and emissions in the transportation sector. This paper reviews the key technologies and comprehensive management strategy of new energy HEVs. The key technologies of new energy HEVs include battery technology, power technology, and comprehensive management strategy. Battery technology must provide high energy density, long cycle life, and high power density, while power technology must provide high efficiency, low emissions, and smooth power delivery. The comprehensive management strategy includes energy management control and a battery thermal management system, which optimize the battery's energy flow and temperature control. The paper discusses the basic principles and components of new energy HEVs and examines the developments and research in each technology. The article also explores the challenges and opportunities of new energy HEVs. It concludes that the development and adoption of new energy HEVs are essential for achieving a sustainable transportation system and reducing the transportation sector's environmental impact.

Keywords: New energy hybrid electric vehicles, Battery technology, Power Technology

1. Introduction

As worldwide environmental issues worsen, there is a strong correlation between the regularity and quantity of automobile use. Traditional vehicles primarily use oil as fuel, but because oil is a non-renewable non-clean energy, growing oil usage not only leads to increased oil extraction, but car exhaust fumes also contribute to further degradation of the environment. New energy hybrid electric vehicles have gained significant attention in recent years, as they offer a promising solution for reducing carbon emissions and improving fuel efficiency. A hybrid electric vehicle (HEV) is a combination of an electric vehicle (EV) and an internal combustion engine (ICE) vehicle [1]. The HEV can operate on electric power only, gasoline power only, or a combination of both. The battery-powered electric motor provides propulsion, while the ICE serves as a generator to recharge the battery and supply additional power when needed. The HEV system provides improved fuel efficiency, lower emissions, and better performance than ICE vehicles [2,3].

The development of new energy hybrid electric vehicles has been driven by the need to reduce greenhouse gas emissions and improve fuel economy. Governments worldwide have implemented various regulations and incentives to encourage the adoption of new energy vehicles. For example, in the United States, the Corporate Average Fuel Economy (CAFE) standards require automakers to increase their fleet average fuel economy to 54.5 miles per gallon by 2025. Similarly, in Europe, the European Union (EU) has set a target to reduce greenhouse gas emissions by 40% by 2030 compared to 1990 levels [4]. The application of new energy vehicles allows cars to run without relying solely on fuel energy such as oil and can be powered by cleaner energy sources. However, using batteries in purely electric vehicles has a life span. In the long-term use of pure electric vehicles, the generation of many end-of-life batteries will cause a waste of energy, such as lithium, which does not play a role in the actual conservation of energy and resources. However, the support of hybrid technology can reduce the car's excessive dependence on electricity and the annual output of end-of-life batteries. To a certain extent, lithium energy plays a role in saving [5].

Developing new energy hybrid electric vehicles is a complex process that requires the integration of various key technologies and comprehensive management strategies. This paper will discuss the key technologies and comprehensive management strategies of new energy hybrid electric vehicles.

2. Key technologies of new energy hybrid electric Vehicle

The key technologies of new energy hybrid electric vehicles include battery technology and power technology.

2.1 Basic principle

The basic principle of new energy hybrid electric vehicles is to combine the advantages of the electric motor and the internal combustion engine. It refers to the combination of an electric motor and auxiliary power unit in a car to drive the vehicle, which is different from the single internal combustion engine of the car. The electric motor provides propulsion, while the internal combustion engine serves as a generator to recharge the battery and supply additional power when needed. The battery-powered electric motor can operate on electric power only, gasoline power only, or a combination of both. The HEV system provides improved fuel efficiency, lower emissions, and better performance than traditional ICE vehicles.

The new energy hybrid electric vehicle system generally consists of the following basic parts:

Electric Motor: The electric motor provides propulsion to the vehicle. It converts electrical energy stored in the battery to mechanical energy to drive the wheels. Battery: The battery stores electrical energy and provides power to the electric motor. The internal combustion engine or regenerative braking can charge the rechargeable battery. Internal Combustion Engine: The internal combustion engine serves as a generator to recharge the battery and supply additional power when needed. Power Control Unit: The power control unit manages the flow of energy between the battery, the electric motor, and the internal combustion engine. Transmission: The transmission transfers power from the electric motor or the internal combustion engine to the wheels [6], as shown in Figure 1.

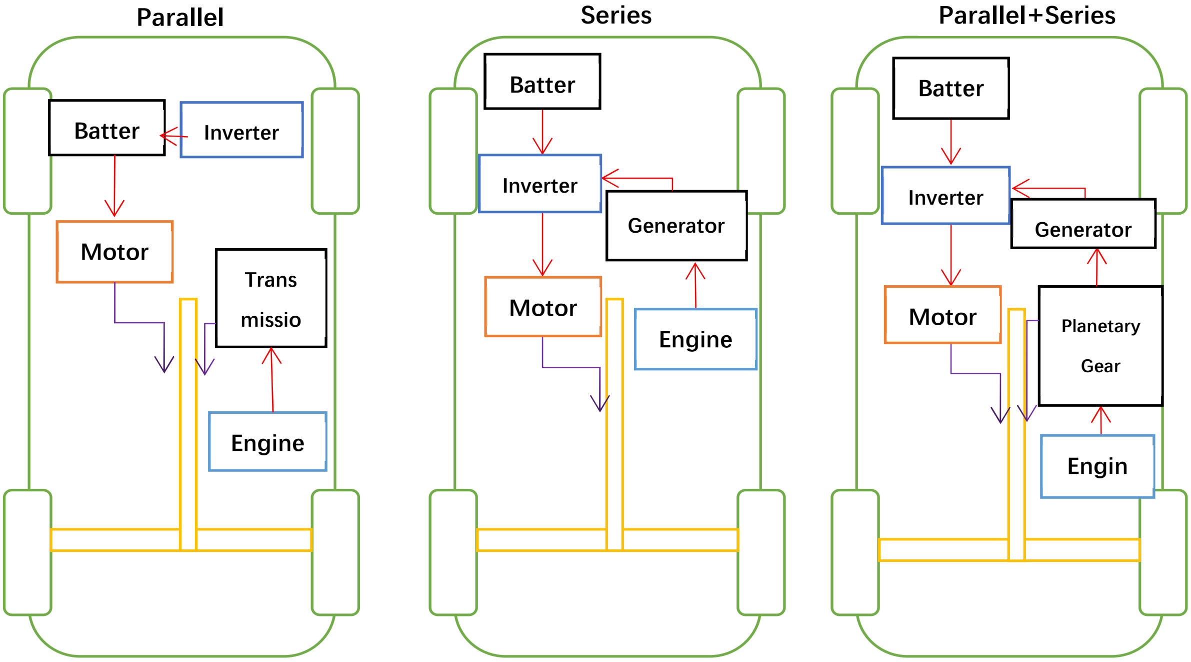

Fig. 1. Parallel, Series, and Parallel-Series dynamic structure analysis diagram of HEVs

The current propulsion power system of hybrid electric vehicles can be categorized into three design types based on the driving form of the car, namely series hybrid, parallel hybrid, and series-parallel hybrid. This classification is determined by the specific vehicle use requirements and energy demand methods during the design process [7]. Each hybrid mode has different operating modes, such as electric, hybrid, battery, or regenerative system for parallel hybrid mode. Furthermore, hybrids can be classified as plug-in or non-plug-in types, each offering advantages in energy environmental protection and battery cost-saving. There are also different levels of hybrid categories, including micro, mild, and full hybrid models, which have varying effects on energy savings, emission reduction, and driving performance during specific car use.

2.2 Battery technology

The battery is one of the key technologies of new energy hybrid electric vehicles. The battery technology used in HEVs must provide high energy density, long cycle life, and high power density. The battery must also operate under various temperatures and environmental conditions. Several types of batteries can be used in HEVs, including nickel-metal hydride (NiMH), lithium-ion (Li-ion), and solid-state batteries. NiMH batteries have high energy density, long cycle life, and low cost. However, NiMH batteries have a lower power density than Li-ion batteries, which limits their use in HEVs with high power requirements [8].

Li-ion batteries are commonly used due to their superior characteristics, such as a lower self-discharge rate, higher energy density, and power density than NiMH batteries. Moreover, they are more durable and have a longer cycle life. However, Li-ion batteries are more costly than NiMH batteries and have a shorter lifespan at high temperatures.

Optimal charging and discharging temperatures generate significant heat, leading to a continuous increase in battery temperature. When the battery's temperature exceeds its safe operating temperature, it experiences discharge, resulting in a dramatic drop in capacity and the inability to complete charging. Temperature-control measures are typically necessary to maintain proper battery function [9]. During low-temperature charging in winter, for example, lithium plating can occur, leading to decreased battery performance and a shortened lifespan. Therefore, it is necessary to heat the battery. A typical battery system includes liquid cooling plates at the module's bottom, connected by pipes to form a circulating heating and cooling system with components such as a circulating pump, heat exchanger, and water heater [10]. To cool the battery during high temperatures, the air conditioning system and water pump are activated, and the heat exchanger cools the cooling medium, which flows through the battery pack to exchange heat and remove heat from the battery. Conversely, when the battery needs to be heated during low temperatures, the water pump and water heater are turned on, and the heated cooling medium circulates through the liquid cold plate to warm the battery.

Battery manufacturers primarily utilize two structural forms for the battery liquid cold plates. The first type is the microchannel tube, consisting of an aluminum alloy porous flat tube brazed with the collecting tube at both ends [11]. While this structure is lightweight, it lacks inherent rigidity and requires additional support from structural components to ensure proper heat conduction by pressing the flat tube against the module bottom. The second type is the double-layer stamped plate structure, composed of a flat upper aluminum plate and a lower aluminum plate with a stamped runner structure. The two aluminum layers are connected through high-temperature brazing, and the flow channel design of this structure offers greater flexibility to accommodate the irregular arrangement of modules within the battery pack.

Irrespective of whether the battery pack features a microchannel tube or stamped plate design, if the liquid cooling plate positioned inside the pack starts leaking coolant, it can lead to a short circuit or a potential fire [12]. Moreover, in most liquid cooling solutions, the branch flow channels have a fixed flow distribution, and the coolant supply cannot be adjusted flexibly to cater to the cooling demands of different modules, causing inconsistent cooling rates among partitions and elevating the internal temperature variation in the battery system. Consequently, this study aims to investigate a new liquid cooling system for lithium batteries intended to resolve the battery's thermal management system.

Solid-state batteries, the third type of battery, hold great potential as a technology for hybrid electric vehicles (HEVs) due to their higher energy density, faster charging, and longer cycle life than Li-ion batteries. Despite these advantages, solid-state batteries are currently still in the developmental phase.

2.3 Power technology

For hybrid electric vehicles (HEVs) to perform optimally, their power technology must offer several features, including efficient energy use, minimal emissions, and seamless power transfer. This power technology encompasses components such as the internal combustion engine, power control unit, transmission, and electric motor, which may be a permanent magnet synchronous motor (PMSM), an induction motor, or a switched reluctance motor. PMSM motors are commonly favored due to their superior efficiency, high power density, and seamless power delivery [13]. HEVs require an internal combustion engine to achieve high efficiency, minimize emissions, and reduce noise levels. These engines can come in the form of gasoline, diesel, or hybrid engines that combine gasoline and electric power to enhance fuel efficiency and reduce emissions. Similarly, the transmission used in HEVs must also be optimized to ensure high efficiency, smooth power delivery, and low noise. HEVs can utilize a variety of transmissions, including single-speed, multi-speed, or continuously variable transmissions (CVTs). Due to their ability to provide excellent efficiency and smooth power delivery, CVTs are commonly utilized in HEVs. A comprehensive management strategy that includes energy management control and a battery thermal management system is necessary to achieve optimal performance in new energy hybrid electric vehicles.

3. Comprehensive management strategy

To achieve optimal performance for new energy hybrid electric vehicles, it's crucial to have a comprehensive management strategy in place. This strategy should encompass energy management control and a battery thermal management system.

3.1 Energy management control

The flow of energy among the battery, electric motor, and internal combustion engine is managed by the energy management system (EMS), which is designed to optimize energy flow for maximum fuel efficiency and performance of the hybrid electric vehicle (HEV) system [14]. The EMS continuously monitors driving conditions like speed, acceleration, and terrain and adjusts power distribution accordingly, using advanced algorithms and predictive modeling to minimize energy losses. Regenerative braking is incorporated in the EMS, which captures the kinetic energy generated during braking and converts it into electrical energy to recharge the battery.

An idle-stop system is also included in the EMS, which automatically turns off the internal combustion engine when idle to minimize fuel consumption and emissions. The engine restarts automatically once the accelerator pedal is pressed. Depending on various control objectives and considerations, the energy management system can be categorized into two types of EMSs: Classical EMSs and ITS-based EMSs.

Classical EMSs are categorized into two modes, namely, rule-based and optimization-based modes. Among the two, rule-based is the earliest and most easily developed control method for HEVs. Rule-based EMSs operate based on the load level and coordinate the internal combustion engine (ICE) operation using electromagnetism [15]. The aim is to shift the working point of the ICE from the low-efficiency region to its high-efficiency region, thereby achieving better fuel economy or emission performance. Rule-based EMSs can be further divided into two types, namely Deterministic Rule-based EMS and Fuzzy Rule-based EMS. Deterministic Rule-based EMS uses heuristic-based and typically has no a priori knowledge derived from the driving cycle. It combines charger sustaining (CS), electric vehicle, charging depletion (CD), and traditional modes in different combinations and time cycles. The system manages the series hybrid powertrain's switch, which functions at its most efficient operating point by using a preset threshold of the battery state of charge (SOC). The strategy activates the engine and generator unit when the battery SOC approaches a low threshold [16]. On the other hand, when the battery SOC approaches the upper limit threshold, the engine is switched off. Although the Deterministic Rule-based EMS is convenient for establishing low computational effort, it cannot adjust to various operating conditions and actual dynamic changes, resulting in suboptimal fuel economy of HEV/PHEV. It is frequently combined with fuzzy control for use in HEV/PHEV to achieve better performance and adaptability of EMS.

The Fuzzy Rule-based EMS is a nonlinear control technique that provides robustness and adaptivity. Its adaptivity stems from the simple modification of fuzzy rules, and its robustness comes from its capacity to endure imprecise measurements and component variances. The Fuzzy Rule-based approach is well-suited for serving as the EMS for HEV/PHEV because it determines the power allocation between the ICE and battery pack, ensuring that the engine runs at maximum efficiency or with minimal emissions.

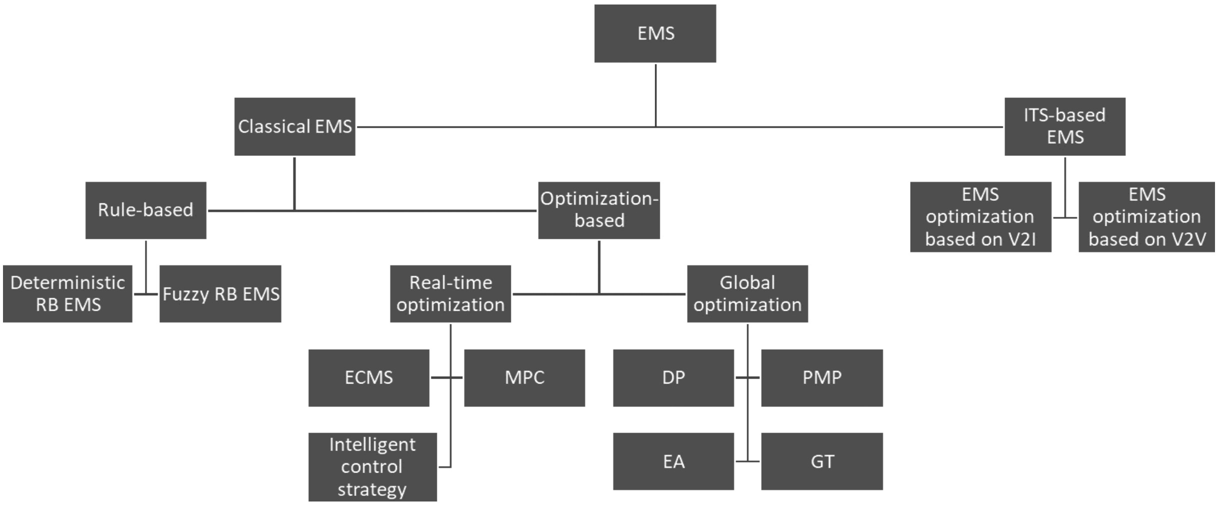

Fig. 2. Systematization diagram of Classical HEVs

Optimization-based energy management systems (EMSs) achieve their control objectives by strictly adhering to constraints while minimizing a cost function. The key control objectives for hybrid electric vehicles (HEV)/ plug-in hybrid electric vehicles (PHEV) are fuel or energy consumption. This paper categorizes Optimization-based EMSs into Global Optimization Method and Real-time Optimization Method [17], as shown in Figure 2.

EMSs, which are global optimization methods, require prior knowledge of the driving cycle. These methods typically employ various intelligent control methods such as dynamic programming (DP), game theory (GT), pontryagin's minimum principle (PMP), evolutionary algorithms (EA), and other methods. DP is a mathematical programming technique that breaks down complex decision-making processes into smaller, single-step problems to optimize EMSs. On the other hand, PMP determines the optimal control signal based on limited constraints on the state or input control while moving from one state to another and has been studied by many researchers for EMS design. EA is a heuristic random search method inspired by natural selection, which conducts swarm search and has strong robustness but suffers from slow convergence and local optimization.

GT is a mathematical model for studying conflicts and cooperation among rational decision-makers and has shown good optimization results. It can be applied in real time and is not dependent on operating conditions or time factors, making it a suitable method for minimizing the global fuel consumption of mixed heavy-duty trucks.

Real-time Optimization is a method used to minimize energy consumption during real-time energy management. This involves finding the optimal working point based on the engine's fuel consumption, power, and efficiency graph. This strategy does not require future driving information or specific driving cycle conditions and has a low computational cost, making it practical. Real-time modes that can be used include ECMS, MPC, and Intelligent control strategy. ECMS involves introducing equivalent factors(EF) and minimizing fuel dependence and EM conversion fuel consumption [18]. Improved ECMS considers the efficiency of ICE, generator, and battery for optimizing overall performance. MPC is widely used in industry and obtains optimal solutions in the prediction domain when having real-time operating potential. The intelligent control strategy is an advanced control theory to solve control problems that are complicated to solve by classical methods. Machine learning, such as artificial neural networks, deep learning, and reinforcement learning, is commonly applied to HEV/PHEV EMSs using this strategy.

Classical EMSs are primarily designed based on standard driving cycles, which differ from actual driving conditions. Consequently, these EMSs cannot achieve optimal fuel efficiency in practical situations due to differences between practical and standard driving cycles. Additionally, the uncertainty of traffic conditions, such as traffic accidents and congestion, makes it challenging for classic EMSs to adapt to various traffic scenarios. However, the emergence of intelligent vehicle technology and ITS presents new opportunities for developing real-time optimized EMSs that guarantee traffic safety. V2V and V2I control methods can provide real-time traffic data and historical information for HEVs, accurately quantifying traffic flow and driving cycle conditions. This accurate input condition is beneficial for optimizing EMSs and improving vehicle performance, maneuverability, safety, and fuel economy.

3.2 Battery thermal management system

The battery thermal management system (BTMS) is essential for maintaining the optimal temperature range of the battery. The BTMS ensures that the battery operates within the optimal temperature range, improving performance and prolonging the battery's life.

The BTMS includes a cooling function and a heating function. The cooling system maintains the optimal temperature range of the battery during high power discharge, which can generate heat and cause thermal runaway. The heating system maintains the optimal temperature range of the battery during low-temperature conditions, which can reduce the performance and life of the battery. The BTMS also includes a thermal management controller, which monitors the battery's temperature and adjusts the cooling and heating systems accordingly [19]. The thermal management controller communicates with the BMS and the EMC system to optimize the battery's energy flow and temperature control.

The previous section on battery technology mentioned that a circulating heating and cooling system is typically incorporated into the BTMS module using a liquid cooling plate system. This system includes a circulating pump, a heat exchanger, and a water heater to prevent losses during battery charging and discharging in unique environments. The two primary structural forms of liquid cooling plates in most battery thermal management systems are micro-channel tubes and double-layer stamped plates. Still, they come with welding technology and fluid leakage risks.

To address these risks, Zeng proposed a research and design plan that led to the development of a new type of battery thermal management system. This new system utilizes an independent winding aluminum tube embedded in an aluminum substrate structure to create a new type of liquid cooling plate.

The thermal management system for the battery pack comprises several components, including a circulating pump, a heat exchanger, a proportional valve, and a liquid cooling flow path. Additionally, there is an integrated PTC heating circuit. The circulating pump functions by driving the cooling medium to circulate. As the cooling medium moves, it absorbs heat within the battery pack and releases it through the heat exchanger, as shown in Figure 3. To ensure effective cooling, the liquid cooling pipeline is split into four routes, as Fig.3 shows, each dedicated to cooling a specific zone within the battery pack. The inlet of each cooling pipe outside the battery pack has a proportional control valve installed. During charging and discharging, the proportional valves regulate the cooling medium's flow rate in real-time, thereby balancing the temperature differences among the module's different zones [20].

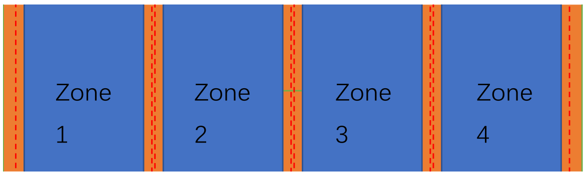

Fig. 3 Schematic diagram of four-way battery pack module arrangement

The liquid cooling plate has a unique structure where aluminum tubes are integrated into an aluminum substrate.

These winding aluminum tubes are formed by bending and shaping a whole aluminum tube and possess excellent malleability. The aluminum substrate is produced through an extrusion molding die and features multiple grooves that align with the outer circle of the aluminum tube, along with rectangular and flat cavities that can hold the heating core. The aluminum tube and substrate are joined through brazing, resulting in an embedded liquid cooling plate. To evaluate the effectiveness of the low-temperature heating system, Zeng compared the integrated heating design proposed in the study and the widely used PTC external circulation heating system for battery packs. The battery pack was initially placed in an environmental chamber and kept warm at a certain temperature for over 24 hours until all modules reached the same temperature. Then, the heater on the liquid cooling plate was turned on, and the heating process was terminated once the battery pack's modules reached the high-current charging temperature. The battery pack was linked to a circulating water pump, a water heater, and a water/refrigerant heat exchanger through pipelines for the PTC external circulation heating system. It was then placed in an environmental chamber and kept warm at the same temperature for more than 24 hours. After that, the water heater and circulating water pump were activated, and the heating process was completed once the battery pack's modules reached the high-current charging temperature. The heating system developed in this study exhibited a 41.4% reduction in heating energy consumption and saved 65.3 minutes compared to the PTC external circulation heating system [21]. This system can quickly reduce the temperature difference among the battery modules, achieving temperature uniformity.

4. Conclusion

Consequently, the development and adoption of new energy hybrid electric vehicles are essential for achieving a sustainable transportation system and reducing the transportation sector's environmental impact. The key technologies of new energy hybrid electric vehicles include battery technology, power technology, and comprehensive management strategy. Battery technology must provide high energy density, long cycle life, and high power density to enable the vehicle to travel long distances while minimizing the weight and size of the battery pack. Power technology must provide high efficiency, low emissions, and smooth power delivery to enhance the driving experience and reduce the environmental impact. A comprehensive management strategy includes energy management control and a battery thermal management system, which optimize the battery's energy flow and temperature control, improving the battery's efficiency and life. Furthermore, adopting new energy hybrid electric vehicles can bring significant benefits, including reduced fuel consumption, emissions and improved air quality. Using regenerative braking and idle-stop systems can reduce fuel consumption and emissions. In contrast, using electric power in low-speed driving can further reduce fuel consumption and emissions. However, there are still challenges and opportunities for further improvement in new energy hybrid electric vehicles. The cost and performance of the battery technology need to be improved to enable wider adoption of new energy hybrid electric vehicles. The infrastructure for charging and servicing new energy hybrid electric vehicles needs to be developed and expanded to support the growth of this technology. Additionally, there is an opportunity to explore integrating new energy hybrid electric vehicles with renewable energy sources, such as solar and wind, to further reduce the transportation sector's environmental impact.

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