Optimizing Hybrid Vehicles: Integrating Engine Dynamics, Energy Technologies, and Management Strategies

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Abstract. With the growing emphasis on environmental protection and the escalating energy crisis, hybrid vehicle technology has rapidly advanced and emerged as a critical focus in today's automotive industry. Combining the features of both traditional and electric vehicles, hybrid technology aims to achieve efficient energy utilization across all speed ranges, enhance the fuel efficiency of conventional vehicles, and significantly improve the driving range and battery cycle life of electric vehicles. This paper elucidates the fundamental working principles of hybrid electric vehicles and examines their crucial energy recovery technologies. Utilizing relevant prediction and planning models, it analyzes energy management strategies for hybrid electric vehicles under various conditions. The findings indicate that compared to traditional energy management strategies, the novel approaches can substantially reduce energy consumption and markedly improve fuel economy. As a transitional solution during the battery technology bottleneck period, hybrid electric vehicle technology holds significant practical value and application potential. Future research should focus on enhancing battery performance, optimizing energy management algorithms, and the comprehensive design of power systems to advance further and popularize hybrid vehicle technology.

Keywords: Hybrid vehicle technology, energy management, hydraulic regenerative braking, motor regenerative braking.

1. Introduction

With the deepening of energy and environmental crises, countries are actively seeking the transformation and upgrading of traditional fuel vehicles and their power systems [1]. With the increasing global demand for sustainable energy, hybrid vehicles are being valued for their potential in energy efficiency and emissions. Due to the randomness of the operating point distribution of fuel engines, it becomes difficult to effectively manage pollution emissions and control driving efficiency for fuel vehicles [2]. Pure electric vehicles have been widely used due to their zero emissions and pollution-free characteristics, becoming representatives of new energy vehicles. However, in the current bottleneck of battery technology development, issues such as insufficient cycle life and limited range of batteries have become key factors hindering the further popularization and application of pure electric vehicles.

Statistics show that during normal driving, traditional cars spend approximately 20% of their time at low speeds or parked. In contrast, hybrid vehicles can utilize their high-power engines to start quickly, thereby reducing energy loss when parked. This design not only reduces the energy consumed due to fuel combustion but also reduces the impact of exhaust emissions from fuel combustion on the environment. Although the limitations of battery technology have affected the popularity of electric vehicles, hybrid vehicles provide a transitional solution that reduces reliance on a single energy source.

At the same time, the range, charging, and safety of pure electric vehicles are temporarily difficult to meet people's needs for long-distance travel. The limited battery capacity, diverse travel needs, and mismatch between charging facilities and demand have gradually become bottlenecks in the development of electric vehicles. These also limit the further promotion and application of pure electric vehicles. Future research will focus on improving battery performance and developing more

advanced energy management algorithms to further enhance the performance and market competitiveness of hybrid vehicles.

This article first outlines how the electric motor and internal combustion engine work together in hybrid power transmission systems, then reviews the research progress of key technologies in existing electro-hydraulic hybrid power systems, analyzes the application of various energy management control algorithms in electro-hydraulic hybrid power systems, and finally explores the possible development trends and future research directions in this field.

2. The Collaborative Working Mechanism of Electric Motors and Internal Combustion Engines in Hybrid Powertrain System

Hybrid electric vehicles are vehicles with multiple driving modes, and their core driving forces include two types: one is traditional power based on the heat generated by the engine, and the second is based on the power provided by generators and batteries. According to the different internal structures, hybrid vehicles can be divided into several types, with the main difference being the number of electric motors and their configuration in the drive system. This article will provide a detailed introduction and analysis of the three currently popular types of hybrid vehicles.

2.1. Series Hybrid Electric Vehicle

The drive system of a series of hybrid electric vehicles consists of an engine, a generator and a drive motor, and these components are connected in series, as shown in Fig. 1. which has the advantages of a simple structure and high operating efficiency but requires a high level of engine performance. The operating principle is that the engine drives the generator to produce electrical energy, which is then converted into mechanical energy to drive the vehicle; when a large amount of mechanical energy is not required (e.g., low-speed driving), the excess is stored by the generator, and when more mechanical energy is required (e.g., acceleration), the generator converts all available electrical energy into mechanical energy to support the vehicle's operation. This design reduces engine runtime, lowering exhaust emissions and fuel consumption, and is particularly suited to city driving, where fuel economy is improved by efficiently utilizing electrical energy storage through frequent starts and stops. However, an efficient energy management system is required to coordinate the energy conversion and storage between the engine and electric motor to ensure overall performance optimization. With increasingly stringent environmental regulations and consumer concerns about fuel economy, this series hybrid design is expected to occupy a significant position in the market in the future.

From this working principle, it can be seen that the generator plays a core role in a series of hybrid vehicles and is crucial for the normal operation of the vehicle. Therefore, this type of hybrid vehicle has high requirements for the performance of the generator.

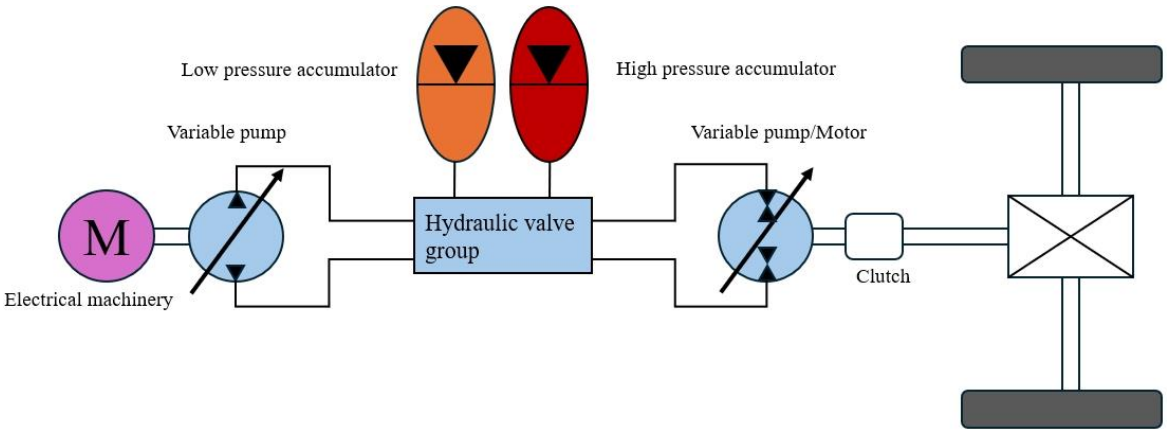


Figure 1. Series electro-hydraulic hybrid powertrain (Photo/Picture credit: Original)

2.2. Parallel Hybrid Electric Vehicle

The parallel hybrid electric vehicle is a combination device of an electric motor connected in parallel with the engine, which is added to traditional gasoline-powered vehicles, as shown in Fig. 2. It has the advantages of small structural modifications and wide adaptability. It is mostly suitable for small and medium-sized vehicles. In this case, when the car is driving normally, it can be powered by either the traditional engine driving the generator to generate electricity, or by the electric motor directly starting it, or by using both methods simultaneously. In this case, not only can the engine pressure be reduced, but it can also ensure that the car has sufficient power. Especially when climbing hills and other situations that require much power, it can reduce the pressure on the engine and minimize the wear and tear of the car.

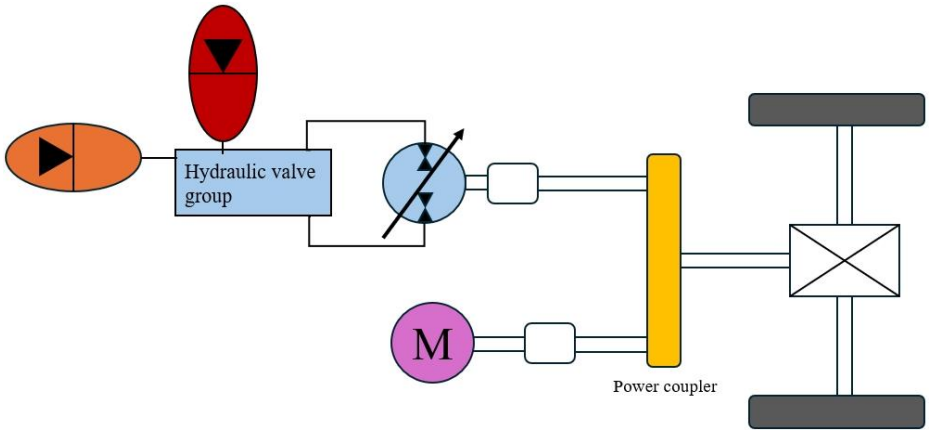


Figure 2. Parallel electro-hydraulic hybrid powertrain (Photo/Picture credit: Original)

2.3. Power-Split Hybrid Electric Vehicle

The Hybrid Electric Vehicle integrates two modes of operation, series and parallel, and is capable of running independently or activating both modes at the same time. Its dual drive system consists of a conventional internal combustion engine system and an electric drive system interconnected by a gear system to provide full performance, as shown in Fig. 3. This vehicle is the most widely used type of hybrid electric vehicle, with a complex system architecture that meets diverse consumer needs and significantly improves the vehicle's operating efficiency. By efficiently utilizing both electrical and kinetic energy, the design significantly reduces energy waste and resource dependence. Its powertrain system mainly consists of an engine, a generator, and drive electric power, with an additional engine power distribution device and an inverter to effectively store some of the electric energy and reduce energy loss compared to a conventional hybrid electric vehicle. Hybrid devices have both series and parallel characteristics, and power system types include engine-based forms (engine as the primary power source, electric motor as the auxiliary power source) and electric motor-based forms (electric motor as the primary power source, engine as the auxiliary power source). The design of hybrid electric vehicles combines both series and parallel modes, providing higher operating efficiency and energy utilization, meeting the diverse needs of consumers, and significantly reducing energy waste and resource dependence.

Although the transmission system of a hybrid electric vehicle has a complex structure, it is relatively easy to control. The working principle is as follows: when there is a low power demand, the engine directly drives the car, transferring kinetic energy to the wheels to make the car travel normally. When there is a high demand for power, the engine not only continues to drive the wheels but also distributes some of its kinetic energy to the generator to generate electrical energy. Some of the electrical energy is directly transmitted to the drive system through the electric motor to push the wheels, while the excess electrical energy is stored in the battery for future use. This design enables hybrid electric vehicles to meet different power requirements while effectively utilizing and storing energy, improving overall energy efficiency and driving performance.

The more complex mechanical structure significantly improves its comprehensive energy utilization and recovery efficiency but also increases the complexity of its control and puts forward more stringent requirements for vehicle chassis space and control efficiency [3].

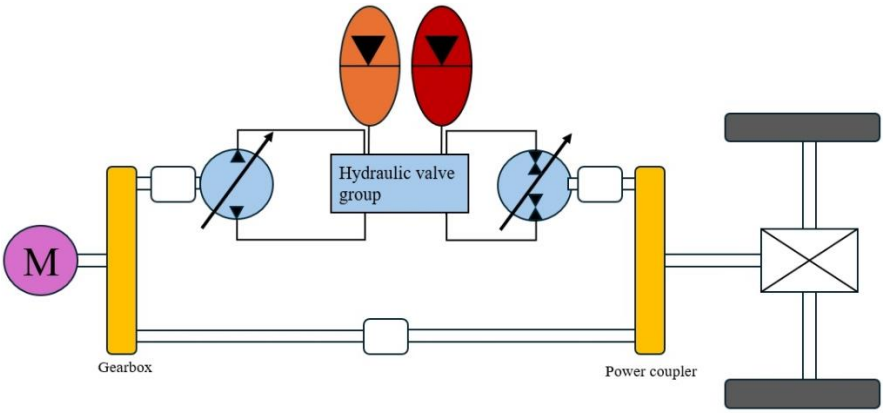


Figure 3. Electro-hydrostatic hydraulic hybrid powertrain (Photo/Picture credit: Original)

3. Energy Recovery Technologies in the Practical Application of Hybrid Electric Vehicles (HEVs)

3.1. Brake Energy Recovery

Traditional cars mainly rely on mechanical braking, which leads to the inability to effectively recover the vehicle's kinetic energy during the braking process, resulting in a significant waste of energy. New energy vehicles, especially those powered by batteries, can recover some braking energy through the regenerative braking function of the electric motor, although this energy recovery method may be affected by external factors such as road conditions.

The electro-hydraulic hybrid power system provides an efficient braking energy recovery solution by combining multiple braking methods such as motor regenerative braking, hydraulic regenerative braking, frictionless hydraulic braking, and mechanical braking. This system not only reduces the wear of the braking system but also significantly improves the efficiency of energy utilization. This article mainly introduces hydraulic regenerative braking and motor regenerative braking.

3.2. Hydraulic Regenerative Braking

When the vehicle is braking or going downhill, the hydraulic pump/motor is pulled in the opposite direction by the axle under the inertia force of the vehicle. Connecting a high-pressure accumulator at the outlet of the pump/motor can quickly establish pressure at its outlet and generate braking torque for the pump/motor. The high-pressure oil output by the pump/motor due to the reverse dragging of the axle is stored in the high-pressure accumulator. The method of converting vehicle kinetic or potential energy into usable hydraulic energy and generating braking torque is called hydraulic regenerative braking.

3.3. Motor Regenerative Braking

Motor regenerative braking refers to the energy recovery process of electric vehicles during braking to extend the driving range. It relies on the motor working in generator mode to charge the battery or supercapacitor in reverse and converts kinetic energy into electrical energy through nonphysical means. For HEVs, motor regenerative braking is its main energy regeneration method.

4. Energy Management Strategies for Hybrid Internal Combustion Engine Systems

Energy management strategy (EMS) is an essential challenge in HEV's design procedure to deal with the power distribution in multiple power source systems to improve the performance of the HEVs. The main task of EMS is controlling and organizing the power flow, energy storage and power generation between subsystems in order to save as much energy as possible and minimize performance indexes such as fuel/electricity consumption, emission etc. [4].

According to reference, this article briefly introduces a new energy management strategy based on the RBF neural network and dynamic programming method [5]. The specific process is as follows: Use the RBF neural network to predict the vehicle speed in the prediction time domain and obtain the required torque of the vehicle based on this. Then, use a dynamic programming method to optimize the prediction time domain and allocate the torque of the engine and motor reasonably.

This strategy was compared with traditional energy management strategies in simulation experiments, and the results showed that it significantly improved fuel economy and reduced energy consumption by about 15.47%. The article verifies the effectiveness of the proposed strategy through simulation analysis of parameters such as engine and motor output torque, battery charging status, and fuel consumption. In the end, the article concludes that this strategy has high practical application potential, but it is still in its infancy and needs further improvement and practical testing in the future.

5. Conclusion

This article studies the coupled working principle of heat engines and electric motors in hybrid electric vehicles and introduces key power recovery technologies. Finally, a novel energy management strategy based on the RBF neural network and dynamic programming method was introduced. Research has shown that optimizing the power distribution and energy recovery in hybrid power transmission systems can effectively improve the energy utilization efficiency and overall performance of vehicles. Firstly, this article provides an overview of the working principles and characteristics of series, parallel, and power-split hybrid electric vehicles. These three types of hybrid vehicles have their focus on the distribution of driving force and the design of power transmission systems, but the common goal is to improve energy efficiency and reduce emissions. Secondly, this article focuses on the application of brake energy recovery technology in hybrid vehicles. By using methods such as motor regenerative braking and hydraulic regenerative braking, the kinetic energy of the vehicle during the braking process can be effectively recovered, reducing energy waste. Finally, this article proposes an energy management strategy based on RBF neural network and dynamic programming method. By predicting vehicle speed and required torque optimizing power flow and energy storage, this strategy has shown significant fuel economy and energy consumption reduction effects in simulation experiments. Although this strategy still needs further improvement and validation in practical applications, its potential to improve the performance and market competitiveness of hybrid vehicles cannot be ignored. In summary, hybrid vehicles, as a transitional solution, have important practical significance and application prospects in the current bottleneck of battery technology development. Future research should continue to focus on improving battery performance, optimizing energy management algorithms, and comprehensive design of power systems to promote the further development and popularization of hybrid vehicle technology.

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