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Hybrid electric vehicles and regenerative braking

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Abstract. With the rapid development of the automotive industry, the fossil fuel crisis and environmental pollution issues have become increasingly severe. The demand for low energy consumption and low emissions has become an inevitable trend in automotive development. Hybrid electric vehicles effectively address the issues of driving range and emissions reduction, making them an important branch of new energy vehicle technology. Electric vehicles have long faced the challenge of limited driving range, particularly in urban driving conditions with frequent start-stop processes. This study focuses on new-energy electric vehicles and proposes an energy recovery control strategy for regenerative braking. Considering various related influencing factors, the strategy accurately allocates the regenerative braking force of the drive motor during vehicle coasting, deceleration, and braking processes. This improves the energy recovery efficiency of the vehicle while ensuring driving safety. This article introduces the operating principles and classification of hybrid electric vehicles and provides an overview of the regenerative braking technology in current hybrid electric vehicles.

Keywords: hybrid electric vehicle, internal combustion engine, regenerative braking, system structure.

1. Introduction

A hybrid electric vehicle (HEV) consists of an internal combustion engine, a power battery, a mechanical transmission system, an electric drive motor, a control system, and an auxiliary power system. Different driving modes are adopted based on the power requirements under various conditions. In 1997, Toyota produced the first commercial HEV, the Prius. In 1999, Honda officially launched the Insight. Now, well-known Japanese automobile brands such as Honda, Toyota, and Lexus are leading the world in HEV technology [1]. In 1998, the major American automakers introduced three hybrid electric cars - the General Motors Precept, Ford Prodigy, and Chrysler Dodge ESX3. In 2004, Ford introduced the hybrid version of the Ford Escape. In recent years, China's FAW Group has achieved significant sales success by producing the Besturn B70 and the CA6120URHI hybrid electric bus, contributing to notable progress in HEVs. Based on the coupling mode of power sources, this article classifies HEVs into three types: parallel, series, and mixed [2].

Regenerative braking originated in the railway system. Since the 1980s, using three-phase AC induction motors as traction motors in AC drive railway vehicles has become increasingly mature. Compared to previous DC drive vehicles, AC drive vehicles have advantages such as high power factor, low harmonic current, and high regenerative braking power. As a result, regenerative braking is widely adopted in AC drive electric locomotives and electric multiple units. Additionally, the regenerative braking circuit of AC drive vehicles is simpler, and there is no need to change the main circuit connection when regenerative braking is applied. This is because when the rotating magnetic field of the induction motor is lower than the rotor speed, a negative slip condition occurs, causing the induction motor to function as an AC generator. Energy recovery technology is crucial for improving the vehicle's driving range, with regenerative braking being the primary method of energy recovery. Research has shown that effective regenerative braking during frequent braking and starting conditions can reduce energy consumption by 15% and improve the driving range by 10% to 30%.

2. Overview of hybrid vehicles

According to the coupling modes of power sources, HEVs can be categorized into three types: series, parallel, and mixed hybrids. In the following section, the article will proceed to describe the basic operational structures of these three different system types in a formal and academic manner [3].

2.1. Principles of series hybrid electric vehicle (SHEV)

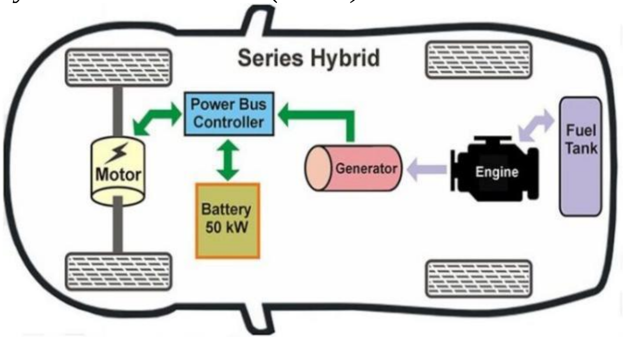

Figure 1. The structure of SHEV, reproduced from the website: https://demotix.com/what-are-hybrid-vehicles-and-how-do-they-work/.

The conventional structural configuration of a series hybrid vehicle involves the engine driving the generator to generate electricity, which is then transmitted through a motor controller to power the motor responsible for propelling the vehicle. In the case of series hybrid vehicles, the driving force is solely derived from the motor. This power system is predominantly employed in urban buses and is less commonly found in passenger cars.

2.2. Principles of parallel hybrid electric vehicle (PHEV)

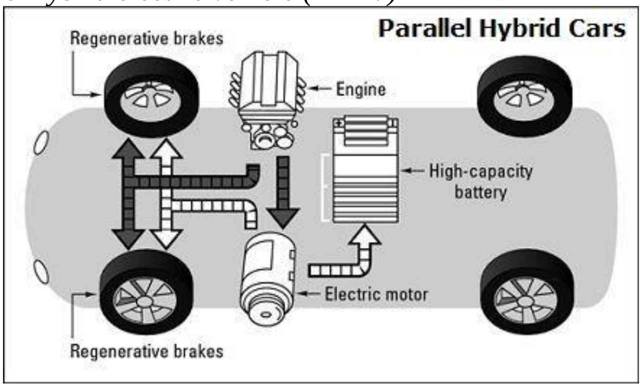

Figure 2. The structure of PHEV, reproduced from the website: https://demotix.com/what-are-hybrid-vehicles-and-how-do-they-work/.

A parallel hybrid electric system comprises a conventional internal combustion engine system and an electric motor system, which can operate in coordination or independently to propel the vehicle. This system offers versatility in various driving conditions, particularly complex ones, due to its ability to switch between different driving modes.

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2.3. Principles of parallel-serial hybrid electric vehicle (PS-HEV)

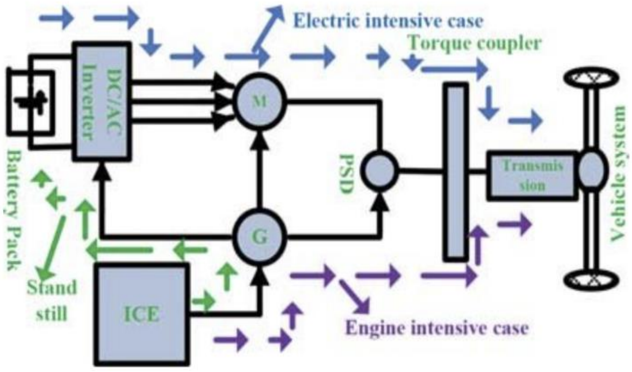

Figure 3. The structure of PS-HEV, reproduced from the website: https://www.researchgate.net/figure /Block-diagram-of-the-parallel-hybrid-electric-vehicle_fig4_321185227.

The series-parallel hybrid system stands out for its distinct characteristic of employing separate mechanical transmission mechanisms for both the internal combustion engine and the electric motor. These mechanisms can be interconnected through a gear system or integrated through a planetary gear structure. This arrangement facilitates comprehensive control over the speed relationship between the two power sources [4].

2.4. The characteristics of HEVs

At present, hybrid vehicles commonly utilize electric and thermal hybridization. This hybrid approach largely satisfies the car owners' transportation needs and maximizes organic integration without affecting public mobility, thereby achieving energy savings and emission reductions during vehicle operations. In the practical design process, hybrid vehicles incorporate the comprehensive utilization of the engine, generator, and battery. This design advantage does not compromise the car owners' regular driving requirements while effectively enhancing the vehicle's fuel efficiency and performance, highlighting hybrid vehicles' advantages. Moreover, with modern intelligent technologies, hybrid vehicles can adjust the system design to meet the car owners' power requirements and driving conditions [5]. For instance, when the car owner requires higher power during driving, the battery provides the energy. However, when the car owner does not need additional power, the engine operates within the efficient range and stores the excess energy in the battery. This design advantage significantly promotes intelligent and user-friendly energy conservation, allowing personalized driving based on the car owners' habits. Additionally, in the ongoing phase of hybrid vehicle research and development, future advancements may lead to zero carbon emissions or the utilization of alternative biofuels as driving power, further enhancing the superiority of hybrid vehicles and significantly contributing to energy savings and emissions reductions [6].

3. The current development status of HEVs

3.1. Immaturity of HEVs technology

China has researched new energy HEV technology for over a decade. Through long-term research efforts, China's relevant technologies have experienced rapid development, gradually reaching the forefront of the field. In the current context of advocating green development concepts and increasing demand for new energy vehicles by automobile users, automotive manufacturers have been paying more attention to the research and application of advanced and modern HEV technologies in their designs. Notably, leading Chinese new energy vehicles manufacturers such as Xiaopeng Motors and BYD have successively introduced domestically innovative new energy hybrid electric technologies in recent years, significantly improving the development quality and advantages of new energy HEVs. Supported by relevant policies in China, HEVs have achieved mass production and significant sales results. In particular, the government's implementation of tax exemptions and subsidies for purchasing new energy vehicles in previous years has stimulated market demand and encouraged technological research and development by relevant companies, resulting in the rapid and mature development of HEV technology in China [7].

3.2. High market acceptance

HEVs have been successfully launched in the market, triggering a wave of enthusiasm for purchasing new energy vehicles. In particular, the maturity of China's new energy HEV technology has resulted in many HEVs offering better cost-effectiveness and durability than traditional new and gasoline-powered vehicles. As a result, the number of annual HEV purchases in China has been gradually increasing and showing a doubling trend [8]. For example, in 2021, HEV sales in China exceeded 660,000 units, representing a year-on-year growth of over 30%. It vividly demonstrates the market acceptance of HEVs in China and objectively reflect car owners' support level, especially considering the significant share of short-distance urban commuting in daily life. The daily usage of HEVs adequately meets the short-distance transportation needs of typical households. With advantages such as lower maintenance costs and reduced operating expenses, HEVs are gaining popularity and displaying high market acceptance. Looking ahead, it can be projected that by 2030, HEVs will dominate the Chinese automotive market, becoming a significant driving force for the development of the automotive industry. Furthermore, based on the 2021 purchasing trends, domestic brands such as BYD, Li Xiang ONE and GAC Aion are experiencing increasing HEV purchases, which objectively reflects the growing trend of high market acceptance among the public towards HEVs.

3.3. Existing problems

Traditional HEVs: Traditionally, the core objective of HEVs has been to reduce fuel consumption and improve fuel economy. As a result, they may suffer from relatively weak power output and slightly inferior driving performance. Additionally, the absence of a significant all-electric range limits their ability to quickly transition into an era of pure electric driving [9].

Plug-in Hybrid Electric Vehicles (PHEVs): PHEVs face challenges in accurately reflecting fuel efficiency in all-electric modes. The officially rated fuel consumption per 100 kilometers (or equivalent) can significantly differ from the actual driving range, especially when the battery charge is low. In such cases, the energy-saving benefits of PHEVs are often compromised. The limited availability of slow-charging infrastructure in cities further complicates the issue, making charging challenging and hindering the growth of PHEV sales.

Charging Infrastructure: The lack of a well-developed charging infrastructure, particularly for PHEVs, poses a significant challenge. Insufficient charging stations, especially for slow-charging options, hinder the widespread adoption of HEVs. This infrastructure gap affects the convenience and practicality of owning and using PHEVs.

Cost: The current market prices of plug-in hybrid electric vehicles are generally higher than their gasoline counterparts in the same segment. Reducing the cost of plug-in hybrids while maintaining their performance and features remains a key factor in increasing sales [10].

Addressing these challenges requires continued research and development efforts to enhance the power and driving experience of HEVs, improve the accuracy of fuel consumption ratings for PHEVs, expand the charging infrastructure network, and work towards cost reduction in the production of HEVs.

4. Regenerative braking

4.1. Composition of the regenerative braking system

The regenerative braking system in HEVs is a significant component that facilitates energy recovery during braking. The regenerative braking system refers to the process where the potential and kinetic energy stored in the vehicle is converted into electrical energy by the electric motor during braking or

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downhill driving and subsequently stored in the energy storage device. The regenerative braking system consists of the drive wheels, main reducer, transmission, electric motor, AC/DC converter, DC/DC converter, energy storage system, and controller.

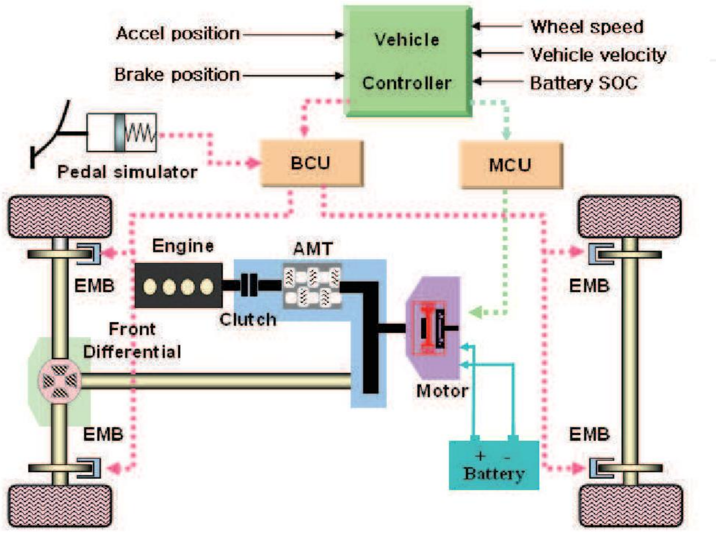

Figure 4. The structure of the regenerative braking system, reproduced from the website: https://www.researchgate.net/figure/Structure-of-single-axle-series-regenerative-braking-system_fig1_273913694.

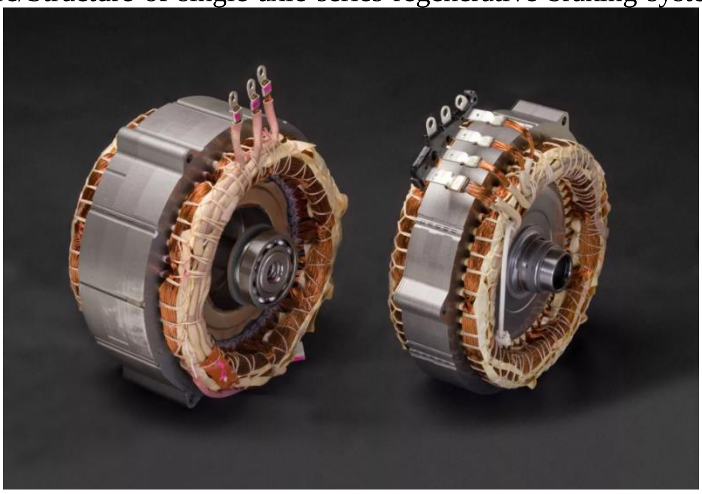

Figure 5. Motor/Generator (M/G) set, reproduced from the website: https://www.treehugger.com/how-does-regenerative-braking-work-85465.

4.2. Principle of operation of the regenerative braking system

During vehicle braking, the greater the proportion of regenerative braking force to the total braking force, the higher the regenerative braking power. This reduces friction losses at the brakes, resulting in more energy stored in the battery when the braking process ends and higher regenerative braking efficiency. The process of regenerative braking energy recovery is as follows:

i) At the beginning of braking, the energy management system sends the power battery's state of charge (SOC) value to the brake controller. When SOC is greater than 0.8, regenerative braking is canceled. When $0.7 \leq SOC \leq 0.8$, regenerative braking is limited by the maximum charging current allowed by the battery. When SOC is less than 0.7, regenerative braking is not limited by the maximum charging current allowed by the battery.

ii) The brake controller receives the master cylinder pressure signal from the pressure sensor and calculates the desired upper limit of the motor regenerative braking intensity.

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iii) The brake controller calculates the actual braking intensity the motor can provide based on the motor speed.

iv) The desired upper limit of the motor regenerative braking intensity and the actual braking intensity that the motor can provide are compared, and the result is sent as an electrical signal to the motor controller.

v) At this point, the motor operates in generator mode, providing a constant current flow with a controlled voltage. The voltage generated by the motor is limited by the inverter and boosted to meet the current output requirements for charging the power battery pack.

4.3. Factors influencing regenerative braking energy recovery

Driving conditions: Higher efficiency is achieved during frequent braking at lower intensities, such as in urban driving with frequent stops and starts. Motor characteristics: The motor's efficiency and operating state directly affect regenerative braking energy's total amount and recovery rate. Battery characteristics: The battery's charge, health, and power state significantly influence energy recovery.

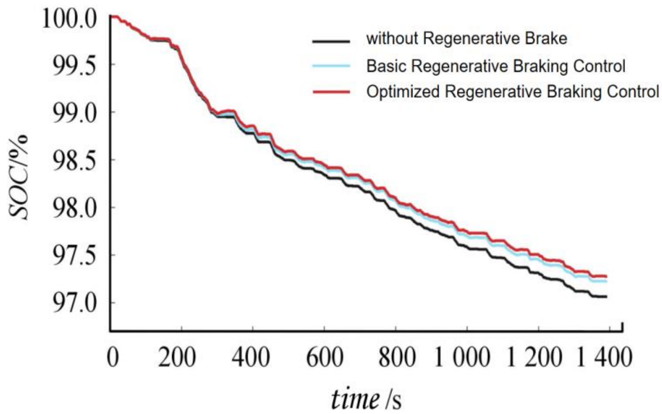

Figure 6. Simulation curve of SOC for the power battery [4].

5. Conclusions

HEVs are currently one of the mature technologies in the field of new energy vehicles, as they address the issue of limited driving range and offer relatively well-developed solutions. With the increasing stringency of regulations related to fossil fuel scarcity and environmental pollution, there is still significant room for improvement in various aspects of HEV technology. Given the dual conditions of policy guidance and tightening regulations on fuel consumption and emissions, significant societal resources are being invested in the new energy vehicle industry. This will contribute to the rapid and substantial development of HEV technology. HEVs are a transitional bridge from traditional internal combustion engines to fully electric vehicles. Their mission is to gradually replace traditional fuel-powered cars. According to the roadmap released by the Society of Automotive Engineers of China, by 2035, all traditional energy-powered passenger vehicles will be converted to hybrid electric vehicles. At that time, the sales ratio between new hybrid electric vehicles and fully electric vehicles is expected to be 50% each. In the next 15 years, the competition in the hybrid electric vehicle market will be extremely intense. There are vast market prospects and high practical value for a significant time. HEVs will continue to play a crucial role in the automotive industry, driving the transition towards greener and more sustainable transportation.

Regenerative braking technology can reduce energy losses during the braking process in HEVs, thereby improving their overall driving range. With the continuous development of new technologies, regenerative braking techniques have been continuously improved, allowing for better coordination between regenerative braking and traditional braking performance. This leads to enhanced vehicle usability and safety. With the development of electric vehicles, regenerative braking has been widely applied and has gradually matured from theoretical analysis to design implementation. Future work will mainly focus on improving and optimizing previous research achievements and gradually increasing industrial applications. This includes the following aspects: Improvement of regenerative braking system structure: Integration into the overall vehicle structure to reduce costs and achieve a streamlined design; Optimization of control strategies: Consideration of energy recovery and braking stability factors, enhancing braking efficiency and increasing energy recovery utilization rates; Continued research on energy storage in electric vehicles: Further study of energy storage systems, including battery management strategies, to achieve comprehensive energy utilization goals. By addressing these areas, regenerative braking systems in electric vehicles can be further enhanced, improving energy efficiency and promoting the sustainable development of the electric vehicle industry.

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