Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA28694

Energy Management and Power Distribution in Hybrid Vehicles

Jiawei Yu

School of Intelligent Manufacturing, Guangzhou Maritime University, Guangzhou, China
yu3815622@gmail.com

Abstract. As new energy technologies continue to evolve, hybrid electric vehicles (HEV) have emerged as a key transitional choice from gasoline-powered vehicles to new energy vehicles, owing to their extended driving range and environmental benefits. This paper systematically summarizes the structure principles of HEV and outlines three currently mainstream energy management strategies, including those based on deterministic and fuzzy control rules, those based on global and instantaneous optimization, and those based on reinforcement learning and deep learning methods. Additionally, this article also compared the performance characteristics of the three system architectures: series, parallel, and hybrid configuration. Through combined simulation studies, this paper explores the fuel economy and system stability under different strategies. Finally, in response to the challenges in complex operating conditions, this paper points out that intelligent and data-driven approaches will play a crucial role in future energy management. This research provides a theoretical foundation and practical insights for the development of more efficient and intelligent energy management systems in hybrid electric vehicles.

Keywords: Hybrid Vehicle, Energy Management, Power Distribution, Power System architecture, Intelligent Control

1. Introduction

As global environmental protection efforts continue to intensify and the shortage of oil resources leads to rising fuel prices, many countries have begun vigorously developing new energy vehicles. However, due to the limitations such as limited battery energy density and underdeveloped rapid charging technology, pure electric vehicles still encounter significant challenges in long-distance driving, high-speed charging, and special conditions like low temperatures and cold weather [1]. In response to this, China will further strengthen technological innovation in vehicle system integration and deepen the R&D structure centered on the "three verticals and three horizontals" framework. Among them, "the verticals" mainly cover plug-in hybrid vehicles, fuel cell vehicles, and pure electric vehicles, thereby establishing a comprehensive technological innovation chain for complete vehicles [2]. At present, the development of hybrid vehicles is relatively mature. They possess both the long-distance travel advantages of traditional fuel vehicles and the environmental benefits of pure electric vehicles, making them a crucial transitional path from conventional gasoline vehicles to new energy vehicles.

DOI: 10.54254/2755-2721/2026.KA28694

Fuel consumption reduction in hybrid vehicles is realized through the collaborative functioning of the electric motor and the internal combustion engine [3]. The primary challenge in hybrid powertrains is to properly manage the coordination among different power sources. Therefore, it is necessary to introduce the concept of Energy Management Strategy (EMS). EMS can be achieved through various methods by employing corresponding algorithms to simulate how the engine, motor, and electric motor can reasonably distribute the energy flow among them under different operating conditions. This approach aims to minimize fuel consumption, emissions, and enhance its power performance. This article focuses on summarizing the prevailing mainstream EMS and power distribution methods in the market. It first introduces the classification, principles, advantages, and disadvantages of the prevailing mainstream energy management approaches in the current context. Subsequently, an analysis was conducted on the strategies for power distribution under various approaches. Furthermore, the challenges currently faced by energy management technology are also discussed. Finally, this paper outlines the future development direction.

2. Working principles and system architectures of hybrid electric vehicles: an overview

2.1. Hybrid power system architecture

The hybrid power system mainly consists of the engine, drive motor, generator, clutch, gear shaft system, differential, motor controller, hydraulic system, etc. It supports multiple operating modes, including all-electric drive, parallel hybrid operation, series hybrid configuration, two-speed engine direct drive, and regenerative braking for energy recovery [4]. It is mainly divided into three configurations: series type, parallel type, and a hybrid of both.

2.2. The basic principle of the hybrid vehicle system

Hybrid electric vehicles (HEV) integrate both an Internal Combustion Engine (ICE) and an Electric Motor (EM) to constitute a unified power system. ICE provides the main driving power and range support. EM participates in driving during high-power demands and enhances fuel efficiency through kinetic energy recovery. The electric motor can recover braking energy or absorb the excess output of the ICE to charge the battery or supercapacitor. The EMS coordinates the power distribution and the energy storage state to achieve a comprehensive optimization of efficiency and performance [5]. The main advantage of the hybrid power system lies in its significant improvement in fuel utilization efficiency while also reducing exhaust emissions. However, its complex design and high cost are also current challenges that need to be overcome.

3. Hybrid vehicle EMS

3.1. Rule-based EMS

The rule-based energy management strategies are currently the most prominent approach, with rules formulated based on engineering experience, experimental data, etc. It generally employs an "if-then" framework, making it commonly applied in real-time energy management. Its computational complexity and logic are relatively simple, and it can be classified based on the clarity of its rules, typically falling into two types. One type is deterministic rule-based EMS, which is fixed and clear. The other type is fuzzy logic rule-based EMS, it possesses a degree of uncertainty and flexibility [6].

DOI: 10.54254/2755-2721/2026.KA28694

3.1.1. Deterministic rule-based EMS

In a deterministic rule-based EMS, thresholds are established according to predetermined factors such as vehicle speed, torque, power demand, and the state of the battery. These parameters define how energy is distributed and which operation mode is adopted in diverse driving situations, thereby further improving the fuel utilization efficiency of the vehicle. It can be classified into thermostat control strategies, power-following control strategies, state machine strategies, etc [6]. This strategy is relatively simple in design and offers good energy-saving effects, thus being widely applied.

Yang et al. conducted research to optimize the rule-based control strategy of the series-parallel hybrid vehicle via joint simulation using Cruise and Simulink. Specifically, by fine-tuning the State of Charge (SOC) threshold, incorporating the series thermal engine mode, and imposing speed limits, etc., they achieved a 6.9% reduction in fuel consumption under the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) conditions. The effectiveness of this optimization was further verified through a chassis dynamometer test [7].

3.1.2. Fuzzy logic rule-driven EMS

The coordination of engine and motor operation in fuzzy logic rule-driven EMS is accomplished through the application of a Fuzzy Logic Controller (FLC). The essence of this strategy lies in establishing a nonlinear relationship between the control input and output. This is accomplished by leveraging fuzzy sets and a rule-based reasoning mechanism. This strategy can be primarily categorized into a conventional fuzzy control strategy, an adaptive fuzzy management strategy, and a predictive fuzzy management strategy [8].

To enhance the performance of fuel cell hybrid vehicles (FCHV), Li et al. compared conventional Power Following Control (PFC) with the Fuzzy Logic Control (FLC). FLC takes the vehicle power demand and the battery SOC as inputs, and adjusts the fuel cell power output to operate within the efficient range and maintain the SOC stable. This experiment is based on a fuzzy rule base and is simulated on the Simulink platform. It is tested under typical driving conditions of Chinese cities and NEDC cycles. The results indicate that FLC outperforms PFC in terms of acceleration performance, maximum speed, and fuel economy. The hydrogen consumption and equivalent fuel consumption decreased by approximately 6.9% and 9.1% respectively, while the SOC fluctuation was more stable and the energy management was more efficient [9].

3.2. Optimization-based EMS

The core task of the Optimized Control Strategy (OCS) is to construct an optimization problem and solve it by using the corresponding optimization methods. During this process, multiple constraints and optimization objectives jointly determine the form of the objective function [10]. The two commonly used optimization strategies at present are: the global optimization method and the instantaneous optimization method.

3.2.1. Global optimization method

The management strategies based on global optimization usually require the assumption that the global interference of the system is known. Based on this assumption, optimization methods including Genetic Algorithms, Dynamic Programming (DP), and Game Theory Methods are utilized to perform searches to improve system-level performance [11]. DP is a commonly used method. It is widely applied in the energy management of hybrid vehicles. Panday et al. pointed out that the

DOI: 10.54254/2755-2721/2026.KA28694

fundamental idea is to recursively break down the original problem into a series of interrelated sub-problems, and then solve them step by step to simplify the overall solution process [12]. This method has both a theoretical foundation in mathematical optimization and the feasibility of implementation in computer programs, thus holding significant practical value in engineering applications.

3.2.2. Instantaneous optimization method

The management strategy based on instantaneous optimization defines an instantaneous cost function at each moment and simultaneously solves the optimal control variable of the vehicle. This control variable can achieve an approximate goal of the global cost function through iteration and rolling optimization [11]. The commonly used methods include the Equivalent Consumption Minimization Strategy (ECMS), Model Predictive Control (MPC) and Pontryagin's Minimum Principle (PMP). Among them, ECMS, as an instantaneous optimization strategy, can achieve the optimal energy distribution among various power sources without relying on global prediction information. Guo et al. developed a coordinated control framework for the front and rear motors of a four-wheel-drive PHEV using the ECMS approach. By introducing an equivalent factor, they transformed electrical energy consumption into an equivalent fuel consumption measure. Taking the minimization of this equivalent fuel usage as the optimization target, the strategy enabled real-time power distribution, ultimately enhancing both fuel economy and overall energy efficiency [13].

3.3. Learning-based EMS

Energy management based on learning has emerged as a novel and popular approach in hybrid vehicle energy optimization in recent years. Its essence lies in leveraging artificial intelligence to refine algorithms. It does not depend on conventional "expert knowledge" or explicit modeling and calculation of the mathematical model of the controlled object. Instead, advanced data mining techniques are leveraged, drawing on both historical and real-time operational datasets to produce predictive insights and establish corresponding control policies [14]. In recent years, Learning-Based EMS has developed rapidly, and it can be primarily categorized into three types: Reinforcement Learning (RL), Deep Learning (DL), and their integration, Deep Reinforcement Learning (DRL).

Guo et al. proposed a reinforcement learning strategy based on Q-learning, which was applied to the energy management of fuel cell hybrid vehicles. The experimental results indicated that the enhanced objective function substantially accelerated the convergence of the training process. By eliminating the battery termination SOC constraint, this approach achieved superior performance in both fuel consumption and control compared with conventional dynamic programming, highlighting the potential of reinforcement learning for real-time energy management [15]. Udeogu et al. proposed an energy management strategy that combines the speed prediction of multiple time series LSTM with ANN-enhanced rule control. In the random combination loop, this approach achieves a speed prediction error of only 0.141% with a computational delay below 1 ms. The ANN dynamically modulates the supercapacitor's power, resulting in a 31.8% increase in energy throughput, a 47.47% reduction in battery peak power, an approximate 27% extension of battery life, and a 22.25% decrease in total energy consumption. For the first time, the battery and supercapacitor SOC were synchronized in discharge, significantly optimizing the operation of the dual energy storage configuration and possessing strong engineering application value [16]. Additionally, Bilgin et al. based on the Toyota Mirai model, proposed a learning energy management

DOI: 10.54254/2755-2721/2026.KA28694

strategy using Deep Q-learning. The multi-objective reward function balances hydrogen consumption, state of charge (SOC), and power fluctuations to enhance fuel cell lifespan and efficiency. The strategy adopted the target network and prioritized experience replay, enhancing the training stability. The experiment demonstrated that the shallow network converges after 50 iterations, achieving a SOC error <3% during the SC03 cycle, reducing power fluctuations by 37%, and decreasing hydrogen consumption by approximately 12%, thereby enabling real-time control in a high-dimensional state space [17].

These three methods each have their own advantages in energy management. Conventional reinforcement learning has a faster training speed and can learn feedback in real time, but it is difficult to handle high-dimensional states. Deep learning, meanwhile, enhances prediction accuracy and battery lifespan, yet lacks the capability for adaptive strategy updates. Deep reinforcement learning combines the characteristics of both, offering more stable control and stronger intelligent learning capabilities, though its operational training process is more complex. Overall, deep reinforcement learning demonstrates greater characteristics and advantages of intelligent learning, and it will be the primary research direction for energy management in hybrid technology in the future.

4. Power distribution of hybrid vehicles

4.1. Composition and structure of hybrid systems

A hybrid vehicle's powertrain mainly comprises an internal combustion engine, an electric motor, a battery pack, and a control system [18]. The structure of its power system is mainly categorized into series, parallel, and series-parallel hybrid. Table 1 illustrates the power distribution characteristics of the three typical architectures.

Table 1. Comparison of typical hybrid system architectures [18]

System Architecture	Technical Features	Advantages	Disadvantages
Series	ICE indirectly powers the vehicle by generating electricity for the electric motor.	Engine runs efficiently with zero emissions and low-speed low noise	Relatively low energy conversion efficiency, especially at high speeds.
Parallel	ICE and electric motor can provide torque simultaneously or independently.	High energy efficiency, fast power response, and compact structure.	Control strategies are complex and highly dependent on energy management systems.
Series-parallel	Engine can drive wheels directly or generate electricity for battery/motor.	Excellent overall performance with adjustable drive modes for balanced power and fuel efficiency.	High system integration, complex control logic, and strict electronic control requirements.

Each of the three methods has its own advantages and disadvantages. For instance, the series connection type has a simple structure and generates less pollution and noise, but its energy conversion efficiency is relatively low. This paper takes the plug-in series hybrid system developed by Anton et al. based on the Volkswagen Golf GTD as an example. Compared with the conventional power system, it reduced fuel consumption by approximately 38% [19]. Whereas the parallel configuration provides higher energy utilization efficiency and greater system stability, but its control strategy is more complex. For single-shaft parallel hybrid vehicles, Qiang et al. proposed the Approximate-ECMS strategy, which minimized fuel consumption while balancing economy and

DOI: 10.54254/2755-2721/2026.KA28694

real-time performance [20]. Zhu et al. achieved efficient multi-energy coordination by rationally allocating parameters and integrating pure electric, series, and parallel switching strategies. Their research indicated that compared to series and parallel configurations, series-parallel vehicles simultaneously offer both power performance and fuel economy, though their system architecture is more complex and manufacturing costs are higher [21]. Therefore, it is essential to select an appropriate system architecture based on vehicle usage requirements and conditions to minimize energy consumption, enhance vehicle economy, and improve energy utilization efficiency.

4.2. Power distribution strategy based on energy management control

In hybrid vehicle systems, the effectiveness of power distribution is often influenced by energy management strategies. To address the coordination challenges among lithium batteries, fuel cells, and supercapacitors, Lei et al. formulated a dual fuzzy logic-based energy management strategy. This strategy employed a primary controller to regulate the fuel cell output, while a secondary controller jointly managed the discharge and energy recovery processes of lithium batteries and supercapacitors based on power differentials and the charge state of energy storage units. This enabled dynamic power allocation among multiple energy sources. The result indicated that under WLTC operating conditions, fuel economy was improved by approximately 6.7% and 6.4% in comparison with the traditional power-following control and single fuzzy control strategies. This method not only effectively reduces the start-stop frequency of the fuel cell and hydrogen consumption but also significantly alleviates the current fluctuations of the lithium battery, further improving the dynamic response performance of the system and the overall energy efficiency [22]. Additionally, He et al. introduced an optimization strategy for power distribution. Unlike conventional strategies, this method employs a nonlinear programming algorithm for optimization, thereby enhancing energy efficiency while simultaneously extending the service life of fuel cells. Through this strategy, the system can achieve more efficient energy distribution while ensuring durability [23].

5. Challenges and development trends of hybrid power technology in the future

With the continuous development of hybrid technology, demands for energy utilization and environmental protection in hybrid vehicles are also rising. Therefore, the research on EMS will become the primary development direction in the field of hybrid technology in the future. The energy management system of hybrid electric vehicles must not only address optimization challenges at the algorithmic level but also tackle multiple challenges stemming from system coupling and engineering implementation difficulties. These include critical issues such as multi-source data fusion, operating condition prediction, control platform adaptation, chip computational capacity, and communication efficiency.

In the future, the research on EMS for hybrid vehicles should focus on several key directions, including: establishing a predictive control framework based on Intelligent Transportation System (ITS), enhancing driving cycle prediction accuracy to more effectively address traffic congestion and variations in road gradients, and integrating higher-precision vehicle dynamics models with actuator response characteristics into real-time control to achieve efficient development and dynamic adaptability of energy management strategies. This paper argues that as artificial intelligence technologies continue to mature, particularly the application of machine learning and reinforcement learning in the automotive energy sector, learning-based energy management strategies will be better positioned to optimize and handle the energy flow and distribution within hybrid powertrain system. By creating machine intelligent agent models, they can autonomously perceive the environment, recognize operating conditions and adjust the energy distribution in real time, thereby significantly improving the efficiency of energy utilization. In the future, learning-based energy management strategies will not only optimize the efficiency of individual power sources but also enhance energy efficiency optimization through multi-energy coordinated control, propelling intelligent hybrid technology to a higher level of sophistication.

6. Conclusion

Against the backdrop of continuous advancements in new energy technologies, enhancing the performance of hybrid vehicles while simultaneously optimizing energy efficiency and controlling exhaust emissions has become a critical issue requiring urgent resolution. This paper systematically arranges existing energy management strategies and power distribution methods in relation to this issue, conducting a comparative analysis of the power performance and energy efficiency of different hybrid powertrain architectures: series, parallel, and mixed hybrid systems. This paper also analyzes energy utilization and power distribution under various strategies during identical operating conditions. On this basis, this paper further points out that the future development direction, particularly in complex operating conditions, should focus on advancing intelligent control, fully leveraging machine learning methods to optimize energy flow and power distribution processes, thereby enhancing the overall system's energy efficiency and environmental adaptability.

References

[1] Wang Weida, Tang Xiaolin, Dong Peng, et al. (2025) Recent Advances and Future Prospects of Vehicle Hybrid Power Technology [J]. Science and Technology Outlook, 4(2): 33-45.
[2] Fu Kuan, Gu Wenjie. (2023) A Brief Discussion on the Classification of Hybrid Electric Vehicle Technologies from Different Perspectives [J]. Times Auto, 2023(8): 17-19.
[3] Tang X, Chen J, Qin Y, et al. (2024) Reinforcement learning-based energy management for hybrid power systems: state-of-the-art survey, review, and perspectives [J]. Chinese Journal of Mechanical Engineering, 2024, 37(1): 43.
[4] Wang Conghe. (2025) Efficiency Analysis and Optimization of Hybrid Power Systems [J]. China Automotive (Chinese-English Edition).
[5] Ehsani M , Singh K V , Bansal H O , et al. (2021) State of the Art and Trends in Electric and Hybrid Electric Vehicles [J].Proceedings of the IEEE, 109(6): 967-984.
[6] Wang F, Hong Y, Zhao X. (2025) Research and Comparative Analysis of Energy Management Strategies for Hybrid Electric Vehicles: A Review [J]. Energies, 18(11): 2873.
[7] Yang Nianjiong, Ran Da, Shi Shengwen. (2023) Research on Rule-Based Optimization of Control Strategies for Hybrid Electric Vehicles [J]. Journal of China Construction Machinery, 21(3): 227-230.
[8] Yao Yongqi, Zhou Yingyu. (2023) Overview of Energy Management Strategies for Hybrid Electric Vehicles Based on Rule-Based Policies [J]. Times Auto, 2023(5): 10-12.
[9] Li D , Xu B , Tian J , et al. (2020) Energy Management Strategy for Fuel Cell and Battery Hybrid Vehicle Based on Fuzzy Logic [J].Processes, 8(8): 882.
[10] Azim Mohseni N , Bayati N , Ebel T (2024) Energy management strategies of hybrid electric vehicles: A comparative review [J].IET Smart Grid, 7(3).
[11] Cao Y , Yao M , Sun X .An (2023) Overview of Modelling and Energy Management Strategies for Hybrid Electric Vehicles [J].Applied Sciences (2076-3417), 13(10).
[12] Panday A, Bansal H O. (2014) A review of optimal energy management strategies for hybrid electric vehicle [J]. International Journal of Vehicular Technology, 2014(1): 160510.
[13] Guo Z, Guo J, Chu L, et al. (2022) A hierarchical energy management strategy for 4WD plug-in hybrid electric vehicles [J]. Machines, 10(10): 947.
[14] Xi J, Ma J, Wang T, et al. (2023) Research on energy management strategy of a hybrid commercial vehicle based on deep reinforcement learning [J]. World Electric Vehicle Journal, 14(10): 294.

DOI: 10.54254/2755-2721/2026.KA28694

[15] Guo L, Li Z, Outbib R. (2021) Reinforcement learning based energy management for fuel cell hybrid electric vehicles [C]//IECON 2021–47th Annual Conference of the IEEE Industrial Electronics Society. IEEE, 2021: 1-6.
[16] Udeogu C U, Lim W. (2022) Improved deep learning-based energy management strategy for battery-supercapacitor hybrid electric vehicle with adaptive velocity prediction [J]. IEEE Access, 10: 133789-133802.
[17] Bilgin T, İzgü S, Yalçin A K, et al. (2024) Energy Management Strategy of Fuel Cell Hybrid Electric Vehicle with Deep Reinforcement Learning [C]//2024 11th International Conference on Electrical and Electronics Engineering (ICEEE). IEEE, 270-274.
[18] Zhang Xiaobo, Liu Qin, Hu Yang, et al. (2025) Design and Optimization of Hybrid Electric Vehicle Powertrains [J]. Internal Combustion Engines and Accessories, 2025(2): 15-17.
[19] Anton B, Florescu A. (2020) Design and development of series-hybrid automotive powertrains [J]. IEEE Access, 8: 226026-226041.
[20] Qiang P, Wu P, Pan T, et al. (2021) Real-time approximate equivalent consumption minimization strategy based on the single-shaft parallel hybrid powertrain [J]. Energies, 14(23): 7919.
[21] Zhu Z, Li C, Tian Y, et al. (2020) Parametric matching and simulation analysis of the series-parallel hybrid electric vehicle [C]//2020 IEEE 5th information technology and mechatronics engineering conference (ITOEC). IEEE, 325-329.
[22] Lei J, Luo W, Huang D, et al. (2022) Dual Fuzzy Energy Control Study of Automotive Fuel Cell Hybrid Power System with Three Energy Sources [J]. Machines, 10(10): 880.
[23] He Y, Miao C, Wu J, et al. (2021) Research on the power distribution method for hybrid power system in the fuel cell vehicle [J]. Energies, 14(3): 734.