

Based on a Comprehensive Review of Energy Management Development in Hybrid Electric Vehicles

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ABSTRACT

To address the challenges of energy and the environment, hybrid vehicles have become a key transitional technology. The core challenge lies in how to intelligently allocate the power between the engine and the electric motor to achieve optimal energy efficiency. The evolution of energy management strategies represents an ongoing endeavor to resolve this complex optimization challenge. A systematic review of its developmental trajectory holds significant guiding importance for driving technological breakthroughs and industrial applications. This study employs a literature review methodology to systematically delineate the developmental trajectory of energy management strategies for hybrid electric vehicles, progressing from rule-based and optimization-based approaches to intelligent predictive control systems. It critically examines the limitations of conventional methods and highlights two major challenges in online optimization: the trade-off between model accuracy and computational efficiency, as well as the coordination of multi-objective optimization. Furthermore, the study synthesizes and evaluates cutting-edge solutions in the field. This study indicates that the field currently faces a core trade-off among model accuracy, computational efficiency, and real-time performance. Existing optimization methods exhibit limitations in addressing system nonlinearities and mode transitions, while vehicle-infrastructure cooperation further amplifies the complexity of multi-objective coordination. Future research should focus on developing high-performance novel mixed-integer solvers and hierarchical intelligent control architectures, signifying a paradigm shift in the field from single-algorithm optimization to system-level collaborative design.

KEYWORDS

New energy automobile; Hybrid power technology; Energy management; Energy recovery

1 Introduction

Amidst the global transformation of the energy structure and the increasing emphasis on environmental protection, the new energy vehicle industry is experiencing unprecedented opportunities for growth. This sector deeply integrates diverse industry dynamics, including the digital economy, cross-boundary innovation, and the servitization of manufacturing, with innovation-driven development serving as the core impetus for its sustained progress and steady expansion. Hybrid Electric Vehicles (HEVs) represent a pivotal transitional technology in the shift from conventional internal combustion engine vehicles to Battery Electric Vehicles (BEVs). By enabling coordinated control of multiple power sources, HEVs synergize the high energy density of internal combustion engines with the high efficiency and clean-operation characteristics of electric motors, thereby overcoming the limitations of single-power-source vehicles in terms of driving range, energy efficiency, and environmental adaptability. Research on hybrid powertrain technology holds significant academic and industrial value. From a technological innovation perspective, it engages with cutting-edge domains such as power coupling design, multi-energy management optimization, and integrated electromechanical-thermal control.

This facilitates the evolution of automotive powertrain systems from conventional mechanical control toward intelligent mechatronic control, accumulating critical experience for the technological iteration of new energy vehicles. In terms of ecological sustainability, the coordinated power management reduces the proportion of inefficient engine operation, enhances fuel economy, and substantially lowers carbon and pollutant emissions—providing a viable technical pathway to support the "dual-carbon" goals and aligning with green transportation policies. From an industrial transition standpoint, hybrid technology does not rely on extensive charging infrastructure and can leverage the existing fuel supply network. Moreover, its core components—power batteries, traction motors, and electronic control systems—share technological origins with those of pure electric vehicles. This not only addresses market adaptability challenges during the current underdeveloped phase of EV infrastructure but also serves as a critical bridge for a smooth industrial transition, offering extensive research prospects and development potential.

2 Literature Review

Yapeng Li's research clearly identifies that the core of parameter matching and energy management in new energy vehicle powertrain systems lies in optimal control problems, and it investigates key challenges including multivariable complexity, multi-state coupling, nonlinearities, and the difficulty in balancing solution accuracy with computational

efficiency.

By establishing nonlinear dynamic system models and convex models, this study employs linear fitting, second-order polynomial fitting, and other methods to quantify relevant indicators. Algorithms such as dynamic programming, equivalent fuel consumption minimization, and convex optimization are applied, alongside experimental validation and real-road data, to evaluate the performance of different strategies. Additionally, an analysis of influencing factors—including the accuracy of the powertrain model, electric motor size, penalty factor, and prediction horizon length—reveals that the convex optimization algorithm effectively achieves fast global optimal solutions. The hierarchical control framework balances solution accuracy with computational efficiency, while the integration of dynamic traffic state information enhances both driving comfort and fuel economy.

The results also demonstrate that model fitting approaches and algorithmic parameter settings have a significant impact on optimization outcomes. Wenbin Yu proposed a battery-super capacitor hybrid energy storage system to optimize performance and lifespan. Firstly, the research scope and core issues of the hybrid energy storage system were defined, and the current research status of its configuration, capacity allocation, and energy management strategies was reviewed through a literature survey. Secondly, a vehicle dynamics model and an equivalent circuit model of the hybrid energy storage were established, and the optimal topology was determined through comparison. Then, based on the vehicle parameters, the key component selection and parameter matching were completed. Subsequently, the NSGA-II algorithm was used to optimize the capacity allocation with battery lifespan and cost per 100 kilometers as the objectives. Finally, a vehicle energy flow model was built based on the WLTP and UDDS driving cycles, and a fuzzy logic energy management strategy was designed and verified through simulation.

The results show that the hybrid energy storage system can effectively "shave peaks and fill valleys", reduce the charging and discharging current and frequency of the battery, significantly extend the battery lifespan, and reduce the system cost.

Compared with the single battery system, it shows better economic and durability performance under different driving conditions. Zhi Liu adopted the bibliometric analysis method to measure the mainstream algorithms and application trends in this field; he constructed an LSTM vehicle speed prediction model based on a heuristic adaptive time span strategy and combined the STM32 embedded system to design a fuzzy adaptive PID control algorithm. The experimental results show that this control strategy can effectively reduce hydrogen consumption per 100 kilometers and improve the overall efficiency of the vehicle, especially in low and medium states of charge, the efficiency optimization effect is significant. The accuracy of vehicle speed prediction and the adaptive control logic are the key factors affecting the energy consumption and efficiency of fuel cell hybrid vehicles. Ran Lü conducted research on the topic of thermal management for new energy vehicles, identifying core issues such as low heating efficiency at low temperatures and complex system architecture. He proposed a multi-heat source vehicle thermal management system based on the hierarchical recovery of waste heat.

By combining component tests with one-dimensional simulation, he built and optimized a simulation model using AMESim to measure system performance and the error of key components. He analyzed the impact of factors such as motor waste heat, ambient temperature, air volume, and PTC power. The results showed that motor waste heat, ambient temperature, indoor condenser air volume, and PTC heating power were the key factors affecting the COP and outlet air temperature of the heating system. Based on this, he developed an energy hierarchical management strategy to achieve flexible switching of heating modes and improve system energy efficiency. The reliability of the optimized simulation model was significantly enhanced. Rule-based strategies overly rely on experience and are difficult to achieve global optimization.

Global optimization methods require complete information on operating conditions in advance and are only suitable for offline analysis. Instantaneous optimization strategies can control in real time but are sensitive to parameters and highly dependent on the accuracy of operating condition predictions. Therefore, it is urgent to explore the combination of global optimization algorithms and fuzzy rules to develop an energy management solution that is easy to implement in engineering and has performance close to the optimal.

3 Method

This study will employ the literature review method to investigate the energy management of new energy vehicles. By drawing on the research of Shengyan Hou on the energy management strategy of the hybrid power system of new energy vehicles, the aim is to enhance the overall energy efficiency of the vehicle, reduce emissions, and extend the system's lifespan through optimizing the power distribution among power sources.

With the increasing complexity of system configurations and the development of connected and intelligent technologies, the design of strategies faces multiple challenges such as real-time performance, adaptability, multi-objective coordination, and computational complexity. Traditional strategies can be classified into rule-based and

optimization-based types. Rule-based strategies (such as threshold rules and state machine logic) have a simple structure and high computational efficiency, and were widely used in mass-produced models in the early days. However, their performance is highly dependent on expert experience and specific operating condition calibration, making it difficult to maintain optimality in variable environments. Therefore, optimization-based methods have gradually developed. Global optimization algorithms represented by dynamic programming can provide a theoretical lower bound of energy consumption for known full-path operating conditions, but they rely on full-path information and have a large computational load, making them unsuitable for direct application in real-time control.

To balance optimality and real-time performance, instantaneous optimization strategies (such as the minimum equivalent fuel consumption strategy) and model predictive control and other online optimization frameworks have received extensive attention. These methods transform the problem into a rolling horizon optimization, making decisions based on limited predictive information, significantly enhancing adaptability to dynamic operating conditions. However, the practical application of online optimization methods still faces two key challenges. First, there is a contradiction between modeling accuracy and solution efficiency. To ensure real-time performance, studies often perform convex approximation or linearization on nonlinear system models, which, while increasing the calculation speed, reduces the model fidelity, especially making it difficult to accurately describe discrete dynamics such as clutch engagement and mode switching, which have significant impacts on actual energy consumption and driving quality. Although mixed-integer programming can uniformly describe discrete and continuous variables, its solution complexity is high and it is difficult to meet the requirements of real-time control frequency. Therefore, developing efficient and accurate mixed-integer nonlinear optimization solution algorithms has become an important research direction. Second, the problem of collaborative optimization of multi-level and multi-time-scale objectives in a connected environment is becoming increasingly prominent.

Vehicle-road coordination technology provides more abundant spatiotemporal information for forward-looking energy management, and the research scope has expanded from power distribution to joint optimization with upper-level decisions such as speed planning and fleet coordination. This leads to a sharp increase in problem dimensions, triggering a "curse of dimensionality" and an exponential increase in computational complexity. How to design an effective hierarchical control architecture, coordinate long-term speed planning with short-term energy distribution, and balance real-time performance and robustness at the algorithm level is a current frontier challenge.

For the power distribution and energy management optimization problem of the hybrid energy storage system in electric vehicles, Li Jiangtao defined the objective centered on enhancing the overall performance and energy utilization efficiency of the system. By combining fuzzy control with a bidirectional full-bridge CLLC resonant converter, the dynamic measurement and regulation of the system's energy flow were carried out, and the influencing factors of the inductance ratio k and quality factor Q on the converter's voltage gain were analyzed. The results show that the reasonable design of k and Q parameters and the energy management strategy based on fuzzy rules are the keys to achieving efficient and stable operation of the hybrid energy storage system. Simulation and hardware experiments further verified that this strategy can effectively coordinate the energy output of the battery and supercapacitor under different working modes and optimize the system performance.

Compared with series and parallel-series hybrid electric vehicles, Jin Chuanqi chose the parallel hybrid electric vehicle as the research object. It has a simple structure, high control flexibility, and a better balance in energy transmission efficiency and power response. The research content focuses on the design and simulation verification of energy management strategies. The author proposed a control strategy based on logic thresholds, taking vehicle speed, required torque, and battery SOC value as input variables.

By setting multiple sets of threshold parameters (such as SOC upper and lower limits, engine efficient zone torque range, etc.), it realizes the intelligent switching of five working modes (pure electric, engine-only drive, hybrid drive, driving charging, regenerative braking). The core idea of this strategy is to prioritize the motor and use the engine as a supplement, and by adjusting the engine load point, it achieves "peak shaving and valley filling" to improve the overall system efficiency. In terms of modeling and simulation, the author built a vehicle dynamics model and key component models based on the Matlab/Simulink platform and used the forward simulation method to simulate the operation process under the NEDC condition. The simulation results show that the designed energy management strategy can improve fuel economy while meeting the power performance requirements, verifying the effectiveness and engineering feasibility of the strategy.

Sun Jingjing systematically expounded the energy recovery control method for series-parallel hybrid electric vehicles, focusing on enhancing the core technical indicator of pure electric range. Firstly, she identified four key factors affecting energy recovery efficiency from the system level: the allowable charging power of the battery, the working capacity of the motor, the hybrid system architecture, and the control strategy and driving conditions. On this basis, she proposed a refined control strategy, clearly dividing the energy recovery function into three working conditions: coasting energy recovery, braking energy recovery, and dynamic switching between the two. She also detailed the torque coordination

logic between the vehicle controller and the brake-by-wire system during the switching process. The core of this strategy lies in prioritizing the use of motor braking to achieve kinetic energy recovery under the premise of ensuring braking safety and driving comfort, with the insufficient part being compensated by hydraulic braking and setting an exit mechanism for high-level function intervention. This control method effectively improves the vehicle's fuel economy and pure electric range.

4 Conclusion

This study, through a systematic review of the evolution of energy management strategies in hybrid power systems of new energy vehicles, reveals the core contradiction that the field is facing among model accuracy, computational efficiency, and real-time requirements.

Although existing research has improved online adaptability by transitioning from rule-based empirical methods to model-based optimization paradigms, with the aid of frameworks such as model predictive control, it is still constrained by the excessive simplification of system nonlinearity and mixed-integer dynamics, especially in effectively handling key issues such as mode switching.

Meanwhile, vehicle-road collaboration technology has expanded the optimization problem to a large vehicle-road-environment system, triggering challenges of multi-time-scale coupling and the "curse of dimensionality". Future breakthroughs will rely on the development of new solvers that can precisely describe the mixed-integer nonlinear characteristics and are computationally efficient, as well as the construction of a hierarchical and collaborative intelligent control architecture to achieve multi-objective collaborative optimization such as safety, economy, and comfort in a connected environment. This indicates that the research focus in this field is shifting from the improvement of individual algorithms to system-level architectural innovation.

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