International Journal of Science and Engineering Applications
Volume 15-Issue 03, 18 – 20, 2026, ISSN:- 2319 - 7560
DOI: 10.7753/IJSEA1503.1004

Research on Energy Management Strategy for Fuel Cell Commercial Vehicles Balancing Service Life and Performance

Shiwei Jin
School of Automobiles and Low-Altitude Unamnned Aerial Vehicles
Zibo Polytechnic University
Zibo, Shandong, China

Abstract: Fuel cell commercial vehicles, owing to their advantages such as long driving range, short refueling time, and zero emissions, are regarded as an important technological pathway for low-carbon transformation in the heavy-duty freight sector. However, the contradiction between the insufficient durability of fuel cell systems and the vehicle's hydrogen economy significantly hinders their large-scale commercial application. The energy management strategy, as the core technology coordinating power distribution between the fuel cell and auxiliary energy sources, directly determines the vehicle's overall performance and the degradation rate of core components. This paper systematically analyzes the degradation mechanisms of fuel cells and traction batteries under commercial vehicle operating conditions, reviews the current mainstream rule-based, optimization-based, and learning-based energy management strategies, and focuses on collaborative control methods that balance service life and performance. Research indicates that multi-objective hierarchical strategies based on health awareness, model predictive control, and reinforcement learning methods can effectively suppress the dynamic degradation of the fuel cell while meeting vehicle power demands, achieving a Pareto optimum between vehicle economy and system durability. This paper provides a theoretical reference for further enhancing the lifecycle economy of fuel cell commercial vehicles.

Keywords: Fuel cell commercial vehicle; Energy management strategy; Service life; Multi-objective optimization; Health awareness

1. INTRODUCTION

The global energy transition and the pursuit of carbon neutrality goals are driving the transportation sector to accelerate its shift towards clean power technologies. Fuel cell commercial vehicles, including city buses and long-haul heavy-duty trucks, demonstrate strong applicability in heavy-duty freight scenarios compared to battery electric vehicles due to their high energy density, short refueling time (10-15 minutes for heavy vehicles), and continuously improving low-temperature start-up performance. However, fuel cell systems still face two core challenges: high cost and insufficient service life. The U.S. Department of Energy has set a target lifespan of 5000 hours for automotive proton exchange membrane fuel cells. However, frequent start-stops, load changes, and high-power output under actual road conditions accelerate stack performance degradation, significantly increasing the lifecycle cost [1].

Fuel cell commercial vehicles typically adopt a hybrid configuration combining a "fuel cell + traction battery" or "fuel cell + supercapacitor" to compensate for the slow dynamic response of the fuel cell and its inability to recover regenerative braking energy. The energy management strategy is responsible for real-time optimal power distribution among multiple energy sources, and its design directly impacts hydrogen consumption and fuel cell degradation rate [2]. Traditional strategies often focus on optimizing a single objective – either minimizing hydrogen consumption or extending fuel cell life – while these two objectives often exhibit a trade-off relationship in actual operation: over-protecting the fuel cell may lead to frequent deep charge/discharge of the battery, whereas unilaterally pursuing system efficiency may exacerbate load fluctuations of the fuel cell.

This paper focuses on the trade-off between "life" and "performance" in energy management strategies for fuel cell commercial vehicles. It systematically analyzes typical hybrid system configurations and component degradation mechanisms, reviews the technical evolution of existing energy management strategies, and specifically discusses control methods for collaborative multi-objective optimization, aiming to provide theoretical support for the development of fuel cell commercial vehicles with enhanced economic viability.

2. FUEL CELL COMMERCIAL VEHICLE POWERTRAIN AND DEGRADATION MECHANISMS

2.1 Typical hybrid system configurations

Current fuel cell commercial vehicles mainly adopt three hybrid topological structures: fuel cell-battery parallel, fuel cell-supercapacitor parallel, and multi-source hybrid combining all three. Among these, the fuel cell-battery configuration, due to its high energy density and technological maturity, is most widely used in buses and long-haul heavy-duty trucks. The introduction of supercapacitors can leverage their high power density to effectively handle transient high-power demands during rapid acceleration and hill climbing, while also smoothing the load fluctuations of the fuel cell [3].

Based on the connection method between the fuel cell and the DC bus, configurations can be classified into direct and indirect types. The direct type omits the DC/DC converter, offering low cost and high reliability, but the fuel cell output voltage is clamped by the bus voltage, making flexible power distribution difficult. The indirect type connects the fuel cell to the bus via a DC/DC converter, decoupling the terminal voltage and providing regulatory freedom for implementing energy management strategies; it is currently the mainstream solution.

2.2 Degradation mechanisms of fuel cells and batteries

The performance degradation of automotive fuel cells mainly stems from the loss of electrochemical active area, catalyst agglomeration and dissolution, and mechanical damage to the proton exchange membrane. In actual operation, frequent load changes, start-stops, high-power output, and idle states all accelerate these degradation processes. Research indicates that the voltage decay rate is the most commonly used engineering indicator for assessing the state of health, capable of reflecting the stack's degradation level online [4].

Traction batteries in hybrid systems serve the function of "peak shaving". Their lifespan is significantly affected by the depth of discharge, charge/discharge rate, and operating temperature. If the energy management strategy causes the battery to operate in deep charge/discharge states for extended periods or fails to effectively control its operating range, it will lead to accelerated battery capacity degradation, thereby weakening its power buffering capability. Therefore, health-coordinated energy management needs to simultaneously focus on the remaining life of both energy sources to avoid premature failure of a single component necessitating the replacement of the entire powertrain system.

3. CURRENT RESEARCH STATUS OF ENERGY MANAGEMENT STRATEGIES

3.1 Rule-based control strategies

Rule-based strategies are the most mature class of methods in engineering applications, including thermostat type, power follower type, and state machine control. Their core logic is to allocate the power output ratio between the fuel cell and battery based on preset thresholds (e.g., battery SOC, power demand) [5]. These strategies are simple in structure, have good real-time performance, and are easy to implement in vehicle control units, thus being widely adopted in early fuel cell vehicle models.

However, the limitation of rule-based strategies lies in their static characteristics: fixed thresholds struggle to adapt to complex and variable actual driving conditions. The power distribution requirements for frequent start-stops in city buses and long-distance high-speed cruising are entirely different, and a single rule cannot achieve optimal control across all conditions. Some studies have attempted to introduce fuzzy logic control, transforming expert experience into fuzzy inference rules, which improves the robustness of the strategy to some extent but still does not break through the fundamental limitation of "fixed rules".

3.2 Optimization-based control strategies

Optimization-based strategies formulate the energy management problem as a mathematical programming problem by constructing objective functions and constraints. Dynamic programming, as a global optimization method, can obtain the theoretical optimal solution under known driving cycles and is therefore widely used as an offline benchmark for comparison. Research shows that incorporating both hydrogen consumption and fuel cell degradation into the objective function of dynamic programming can yield a Pareto frontier solution set that balances economy and durability [6]. For light commercial vehicles, optimization results under different degrees of hybridization and driving cycles indicate that configurations with larger capacity batteries are more conducive to reducing the fuel cell degradation factor.

The Equivalent Consumption Minimization Strategy is a representative method for achieving real-time optimization. It converts the electrical energy consumed by the battery into an equivalent future hydrogen consumption required for replenishment and determines power distribution through instantaneous optimization. Studies on heavy-duty trucks demonstrate that dynamically adjusting the equivalent factor by predicting the battery SOC trajectory using GPS navigation information can improve fuel economy by 1.8% compared to traditional rule-based strategies. Model Predictive Control further introduces a rolling optimization mechanism, solving the optimal control sequence within a limited prediction horizon, balancing global optimization potential and real-time computational feasibility.

3.3 Learning-based control strategies

With the advancement of artificial intelligence, data-driven strategies represented by reinforcement learning have gained significant attention. Reinforcement learning optimizes control strategies through continuous interaction with the environment, requiring no precise system model and exhibiting good adaptability to complex dynamic conditions. A research team from Xihua University proposed a two-layer energy management strategy for multi-stack fuel cell systems in long-haul heavy trucks: the lower layer achieves optimal power distribution between the two stacks, while the upper layer uses Q-learning to coordinate power output between the fuel cell stacks and the traction battery. Hardware-in-the-loop validation shows that the difference in hydrogen consumption per 100 km between this strategy and offline simulation is less than 0.15%, and it effectively maintains battery SOC stability and suppresses fuel cell power fluctuations [7].

Deep reinforcement learning further extends the capability to handle high-dimensional state spaces, but issues such as high training complexity and poor model interpretability limit its practical vehicle application. Current research trends involve combining learning-based methods with rules or optimization algorithms, for example, using fuzzy Q-learning to reduce computational burden while considering system economy and durability.

4. COLLABORATIVE CONTROL METHODS BALANCING LIFE AND PERFORMANCE

4.1 Health-aware energy management

Traditional life-aware strategies primarily aim to slow degradation by limiting the fuel cell power change rate and avoiding low-load and overload operation. However, these methods often neglect the health state of the battery, potentially leading to imbalanced degradation rates between the two energy sources. The core of health-aware strategies lies in introducing the real-time health status of both the fuel cell and the battery into the control objective. Research indicates that after accounting for the additional hydrogen consumption caused by fuel cell degradation, strategies optimizing for equivalent hydrogen consumption can achieve superior overall economics.

Some scholars have proposed a hierarchical architecture based on fuzzy control: the upper layer dynamically adjusts power distribution weights based on the health status of the energy sources, while the lower layer implements real-time power distribution. After optimizing fuzzy controller parameters using genetic algorithms [8], this strategy achieved a significant reduction in fuel cell degradation by 36.7% and a reduction in hydrogen consumption by 25.01% under typical cycle conditions. This result demonstrates that the effective utilization of health status information can substantially enhance system durability without sacrificing economy.

4.2 Online optimization methods for multi-objective collaboration

The challenge in multi-objective collaborative optimization lies in the fact that the trade-off between life and performance is dependent, and fixed weight coefficients cannot maintain optimality across all operating conditions. To address this, offline optimization based on Pareto frontier analysis can provide a benchmark reference for online strategies. For heavy-duty commercial vehicles, due to relatively fixed driving routes, a library of operating condition features can be pre-generated based on historical operational data, enabling offline optimization of control parameters and online retrieval.

The predictive control framework is naturally suited for handling multi-objective optimization problems. By incorporating both fuel cell degradation cost and hydrogen consumption cost into the rolling optimization objective function after unifying the dimensions, and introducing SOC reference trajectory constraints, collaborative optimization of life and economy can be achieved while meeting power demands. The coordinated control of the thermal management system is also noteworthy – stack temperature directly impacts the degradation rate. Integrating thermal management into the unified energy management optimization can further enhance the overall system efficiency.

4.3 Challenges from simulation to real vehicle validation

Currently, most advanced strategies remain at the stage of simulation and hardware-in-the-loop validation, with limited real vehicle validation data available. The transition from simulation to practical vehicle application faces multiple challenges: controller computational power constraints require algorithms to be lightweight; sensor noise and state estimation errors affect control accuracy; and the randomness of actual driving conditions may fall outside the training data distribution. In recent years, real vehicle tests on a 115kW fuel cell heavy-duty truck have shown that hierarchical fuzzy control strategies considering health status can still maintain good effectiveness under real road conditions, providing a positive signal for the engineering implementation of such strategies.

5. CONCLUSION

The energy management strategies for fuel cell commercial vehicles are evolving from single-objective optimization towards life-performance multi-objective collaborative control. Through systematic analysis, this paper draws the following conclusions. The degradation mechanisms of fuel cells and traction batteries are significantly different. Health-aware energy management needs to simultaneously focus on the real-time status of both energy sources to avoid premature failure of a single component affecting overall vehicle economy.Rule-based strategies are highly practical for engineering but have limited optimization potential; optimization-based strategies can obtain theoretical optimal solutions but have high computational burdens; learning-based strategies have strong adaptability but poor interpretability. The fusion of multiple methods – such as combining fuzzy control with genetic algorithms, or reinforcement learning with model predictive control – represents a significant current development direction.

Collaborative control balancing service life and performance has achieved remarkable progress at the simulation and hardware-in-the-loop levels, with some studies achieving over a 36% reduction in fuel cell degradation. Future research directions may include: predictive energy management based on vehicle networking information, coordinated control of multi-stack fuel cell systems, and deeply coupled optimization of energy management and thermal management. With the maturation of online state-of-health estimation technologies and the increase in controller computational power, intelligent energy management systems possessing both high economy and long life are expected to achieve large-scale application in the field of fuel cell commercial vehicles.

6. REFERENCES

[1] WAHAB A, PRAKASH R, SCHOPEN O, et al. Thermal management of fuel cell-battery electric vehicles: challenges and solutions [J]. Applied Energy, 2025, 387: 125635.

[2] LIM H S, KANG B, AHN M, et al. Optimizing hydrogen utilization in fuel cell hybrid vehicles: modeling fuel cell systems and managing energy between batteries and fuel cells [J]. International Journal of Hydrogen Energy, 2025, 99: 819-835.

[3] LUCA R, WHITELEY M, NEVILLE T, et al. Comparative study of energy management systems for a hybrid fuel cell electric vehicle-a novel mutative fuzzy logic controller to prolong fuel cell lifetime [J]. International Journal of Hydrogen Energy, 2022,47 (57): 24042-24058.

[4] ZHOU Y, GUO Y S, YANG F, et al. Speed-prediction-based hierarchical energy management and operating cost analysis for fuel cell hybrid logistic vehicle [J]. Applied Energy, 2025, 390:125843.

[5] WANG Z X, HE H W, PENG J K, et al. A comparative study of deep reinforcement learning based energy management strategy for hybrid electric vehicle[J]. Energy Conversion and Management, 2023, 293: 117442.

[6] JIANG B G, YANG D Y, YU H S, et al. Impact of road gradient on fuel consumption of light duty diesel vehicles[J]. Atmosphere, 2025, 16(2): 143.

[7] FIORI C, ARCIDIACONO V, FONTARAS G, et al. The effect of electrified mobility on the relationship between traffic conditions and energy consumption[J]. Transportation Research Part D: Transport and Environment, 2019, 67: 275-290.

[8] WU X K, FREESE D, CABRERA A, et al. Electric vehicles' energy consumption measurement and estimation[J]. Transportation Research Part D: Transport and Environment, 2015, 34: 52-67.