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Hydrogen Fuel Cell Vehicle Battery Consumption Management Strategy

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Abstract. Hydrogen fuel cell electric vehicles is one of the most significant environmental-friendly modes of transportation. However, having a reliable battery management system is very important. The current battery management systems are not intelligent enough in real life though they can do some basic tasks such as power distribution, fault checking and so on. Besides, they cannot adapt well in different road conditions and driving habits. Previous studies also cannot make adjustments based on the wear of the fuel cells. They certainly do not learn to optimize themselves. Therefore, this paper provided a more advanced battery management system that can adjust its operating mode according to the wear of the fuel cells. In addition, this paper also supposed to optimize parameters based on environmental factors such as weather and road conditions and predict the lifespan of fuel cells through learning historical data. Sharing data from all vehicles can also be achieved so that the system can continually learn and improve, functioning like an intelligent steward that ensures vehicle excellent performance and long lifespan. As a result, hydrogen fuel cell electric vehicles can become more practical, reliable, and widely accepted so that we can achieve a more environmental-friendly transportation system.

Keywords: Hydrogen Vehicles, Battery Management, Lifespan Prediction.

1. Introduction

Today's world, fuel cells are getting more and more important. Many countries are trying to cut carbon emissions and reach carbon neutrality. Therefore, more and more countries are focusing on fuel cells because they are clean, quiet, and durable. They also turn energy into power very efficiently. However, fuel cells still face many problems. These issues make it hard to use them widely. One major problem is the cost of hydrogen production and transportation. Hydrogen is an important fuel for many fuel cell systems. Methods like steam methane reforming or water electrolysis are often chosen to produce hydrogen, which need a lot of energy and advanced equipment. This makes the overall cost high. Moving hydrogen also has difficulties. The two major ways to transport hydrogen are high-pressure gas cylinders and pipelines. Each way needs special equipment and strict safety steps. This adds more cost. Another big concern is the safety risk of hydrogen leaks. Hydrogen can catch fire easily. It will burn when it mixes with air. If a small leak meets a spark or something hot, it will cause a fire or explosion. Also, hydrogen is light and spreads

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quickly. This makes it hard to notice and control when leaked, raising danger to people and equipment.

Therefore, many scholars have studied the development of fuel cell cars from several aspects. Zhou et al. [1] developed a degradation prediction model for PEM fuel cell stacks based on a multiphysical aging model integrated with a particle filter approach, significantly enhancing prediction accuracy for fuel cell performance and lifetime, and offering valuable insights for smart battery management systems. Hu et al. [2] proposed a hybrid method for performance degradation probability prediction of PEM fuel cells, contributing to precise maintenance planning and life assessment. Zheng et al. [3] introduced a brain-inspired computational paradigm for fault diagnosis of PEM fuel cell stacks, providing a novel approach to operational monitoring and fault detection under complex conditions. Zhang et al. [4] proposed a prognostic framework that combines short- and long-term prediction models to estimate the remaining useful life (RUL) of PEM fuel cells more accurately, contributing to improved maintenance planning and system reliability. Cheng et al. [5] developed a hybrid prognostic method for predicting the remaining useful life (RUL) of PEM fuel cells by combining physical modeling with data-driven techniques, significantly enhancing prediction accuracy and adaptability. Li et al. [6] proposed a degradation-adaptive energy management strategy for fuel cell hybrid buses, integrating a recognition-prediction method with a lifetime competition-cooperation control mechanism, which effectively improves the coordination between system efficiency and fuel cell longevity. Liu et al. [7] estimated the remaining useful life of PEM fuel cells using a hybrid method, providing a robust approach for system monitoring and maintenance scheduling. Lu et al. [8] employed a fused unscented Kalman filter approach for performance monitoring and fault accommodation in gas turbines, providing a valuable methodological reference for state estimation and fault-tolerant control in fuel cell systems. Xie et al. [9] investigated fuel cell performance prediction using a particle filter and recurrent neural network fusion structure, offering a robust approach for RUL estimation under variable operating conditions. Hassan et al. [10] summarized the opportunities and challenges of hydrogen fuel cell vehicles, providing a broad perspective on technological and industrial considerations.

Although hydrogen fuel cell efficiency is improved a lot, their performance under real-world conditions remains challenging. Most current models rely too much on lab data. They also cannot adjust to changes in system behavior over time. This limits their practical use and reliability in real-time control. To address this, we propose an adaptive remaining useful life prediction method. It combines data-driven algorithms with system monitoring, which allows the model to continuously learn and adjust using real-time data. Our goal is to improve prediction accuracy and ensure operational safety while lowering maintenance costs. Solving this problem is crucial for making fuel cell electric vehicles more reliable and cost-effective. Accurate life prediction is helpful in making better energy management decisions. It also supports the wider use of hydrogen transportation by building trust in long-term system performance..

2. Challenges in current BMS of FCEVs

The need for clean transportation is growing. Hydrogen fuel cell electric vehicles (FCEVs) have causes huge attention because they have high energy density, fast refueling and long driving range. FCEVs are also used in city buses and logistics projects, which is made from governments to reduce pollution. An important part that makes these vehicles run safely and efficiently is the battery management system (BMS). The BMS controls energy distribution, power output, degradation control and coordinates the fuel cell system. Although control algorithms and hardware have

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improved, current BMS designs still face major challenges. These issues affect long-term reliability and how efficiently the systems operate.

The first challenge lies in the ineffective balance between energy consumption and fuel cell longevity. Current BMS designs cannot well balance short-term power needs with long-term fuel cell health. Many control methods focus on real-time power output, especially during acceleration or high load. However, they do not effectively reduce factors that speed up wear. These include high current density and frequent load changes. For example, a study on hydrogen buses in Beijing found that aggressive driving caused faster membrane drying and catalyst damage. This greatly shortened fuel cell life. Without adaptive control that considers degradation, system life becomes shorter. It also increases long-term operating and maintenance costs.

The second challenge is the poor adaptability of current BMS frameworks under real-world driving conditions. Although they work well in labs or standard tests, they often fail in real environments. Changing temperatures, uneven traffic, and different driving habits can cause problems. For instance, studies in coastal cities like Qingdao showed that high humidity and quick temperature changes often led to fuel cell stack flooding. Current BMS algorithms could not prevent this in real time. This shows that systems must adjust operation parameters based on environmental and driving feedback. They should not only use fixed settings. This problem is also a trade-off between instant power and long-term health. City buses and delivery vans often need high power for acceleration, climbing, or sudden load changes. To meet these needs, many systems let the fuel cell run at high current for short times. Repeated high-current operation stresses the proton-exchange membrane and catalyst layers. This extra stress shortens the stack's life and raises how often maintenance is needed, especially in vehicles used intensively.

The third challenge concerns the limited data-driven learning and self-optimization capabilities of current systems.Most systems use pre-set rules or model-based control. These work well under fixed conditions, but cannot learn from operational data over time. This makes it hard for the system to adapt to aging parts, differences between components, and changes in driving behavior. For example, a study compared FCEVs used for logistics in Shanghai and Shenzhen. It found that even though the vehicles had different usage patterns, they used the same control strategy. This led to either wasted potential or faster wear. Also, most BMS cannot use real-time machine learning or prediction tools. This means control methods do not improve as more data is collected. The lack of data sharing between vehicles also limits learning across whole fleets. This is especially important in large applications like public transport or commercial logistics.

The fourth challenge is fragmented system integration and limited inter-component communication.In many FCEV designs, different subsystems do not communicate well with each other. These include the fuel cell stack, power electronics, thermal management, and battery storage. Often, each subsystem is controlled separately with different update times. This lack of coordination reduces the effectiveness of energy management and fault detection. For example, a field study on fuel cell cars in South Korea found that slow thermal feedback between the stack and cooling system caused short-term performance loss and wasted energy during high power demand. Without unified and timely communication, even small delays in sensor data or actuator response can hurt vehicle performance and increase wear. These technical problems directly impact cost and service. If a fuel cell stack requires unexpected repair or replacement, the vehicle may be unusable for days or weeks. Operators must then use backup vehicles or reduce service. These disruptions increase operating costs and reduce trust in the technology.

Some early users delay software updates or avoid buying expensive sensors to save money. However, this short-term saving often leads to higher costs later. Real-world examples show that for

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hydrogen mobility to grow, BMS strategies must be tested in real fleets. They also need better sensors, diagnostics, and adaptive learning that matches how vehicles are actually used.

These cases show that current BMS designs work well in lab settings, but perform poorly in real-world conditions. To overcome this difficulty, future systems must be more adaptive, predictive, and fully integrated across all vehicle subsystems.

3. BMS performance evaluation

As hydrogen fuel cell electric vehicles (FCEVs) are quite dependent on the BMS, it manages the communication between the fuel cell stack, the power battery and auxiliary systems. Only an outstanding BMS can guarantee a stable energy supply and ensure the durability and reliability. However, with all its obvious benefits, the current BMS implementations still have the following issues that hinder the excellent performance and durability of FCEVs. There are some benefits of current battery management systems.

One of the benefits is that they can distribute energy efficiently and coordinate power. Most BMSs can reasonably distribute power between the fuel cell and the battery according to certain rules. For example, thermostat methods maintain the fuel cell in a favorable range and turn on or off the fuel cell according to the state of charge (SOC) of the battery. When the SOC of the battery is lower than a certain lower limit, the fuel cell turns on to charge the battery and supply power. When the SOC of the battery is higher than a certain upper limit, the battery itself supplies energy. This can avoid unnecessary start-stop times and enhance efficiency. In addition, power-following strategies can maintain the fuel cell working well in real time according to load. When the vehicle accelerates, the battery instantly supplies peak power, and the fuel cell provides stable support. This can protect the stack from high stress. They can work stably under conventional test cycles such as NEDC and CLTC-P and guarantee both efficiency and response.

The second advantage is the coordination at system level. A sophisticated BMS can control the fuel cell, battery and DC/DC converters and thermal system as a whole. The BMS also applies integrated control algorithms to manage energy distribution and operation safety. For example, by continuously measuring voltage, current, temperature and SOC, the BMS can respond dynamically to changes. When temperature in stack rises, the BMS can increase the coolant flow and regulate the power output to the DC/DC converters to reduce thermal stress. This coordination can prevent overheating, reduce degradation and improve reliability. In addition, cloud-edge collaborative BMS and other new technologies can enhance these advantages. They can support low-frequency data collection while alleviating the communication network from heavy traffic. This helps reduce O&M costs while maintaining accurate estimation of SOC and state of health (SOH).

The third advantage is the early fault detection and diagnostic functions that can improve system safety and durability. After analyzing the data such as abnormal current spikes, voltage difference between cells, change of internal pressure and other real-time data, the BMS can find early-stage faults including internal short circuits and lithium plating. Now, most systems still use rule-based algorithms to implement basic diagnostic functions instead of a fully adaptive AI. Although these basic functions are important to trigger immediate protective measures, they do not require a deep understanding of the system. For example, when the BMS detects any anomalies, it will balance the current and voltage, isolate faulty cells, reduce charging limits and trigger thermal management protocols to activate coolant flow or other protections. This kind of proactive monitoring can prevent further damage and reduce the risk of serious failures that would damage the current collectors and other critical components. Electrochemical BMS can provide more powerful monitoring tools with light protection.

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Despite these achievements, there are several limitations. First, current BMSs are lacking proper consideration for the trade-off between short-term efficiency and long-term stack life. Current is based on the immediate demand of the load, and the stack operates at high current density that would accelerate the degradation of the proton exchange membrane and catalyst. It has been demonstrated in studies of hydrogen buses in Beijing that frequent acceleration and heavy loads on the stack would shorten stack life dramatically. Second, current BMSs are not adaptive to real-world driving conditions. The pre-set rules are effective in simple conditions, but are unable to handle different climate, terrain, or driver conditions. For example, in a coastal city like Qingdao, the vehicle would frequently experience start–stop in humid weather, which would easily lead to stack flooding. However, most BMSs are unable to adapt to such conditions and adjust air flow or humidity control automatically. In another example, cars in a congested city would frequently experience start–stop, which would wear the stack. However, most BMSs are unable to adapt to such conditions and set a threshold to reduce the frequency of start–stop. Third, current BMSs are static and do not learn from history. They would not evolve according to their operational history, which means different vehicles in different conditions would adopt the same strategy. Without predictive analytics or inter-vehicle data sharing, it would be difficult to adopt an optimal strategy.

Fourth, current integration among different subsystems is weak. Fuel cell, battery, thermal system, and converter would operate with little coordination. The delay in feedback among different subsystems would lead to a decrease in performance. For example, in South Korea, the cooling feedback was delayed, leading to a decrease in performance when the vehicle was driving under heavy load.

In summary, current hydrogen FCEV BMSs would guarantee basic power allocation, subsystem coordination, and initial fault protection, but are lacking durability awareness, adaptability, self-learning, and integration. Future BMSs should be intelligent, adaptive, and unified, guaranteeing both real-time performance and long-term.

4. Proposed solutions and optimization strategies

To conquer the existing challenges in FCV operations, next-generation BMS should be more adaptable, durable, intelligent, and integrated. This paper distinguish several related solutions and optimization schemes based on the current trends in technology and application.

Firstly, more adaptable operation and longer service life should be achieved. As illustrated in conventional BMS designs, the parameters are usually designed under fixed operation conditions, which will promote faster degradation when the FCV is running under varying conditions. If equipped with predictive health models to monitor the vehicle's health status, such as the degree of membrane dryness, catalyst deactivation, and voltage decay, the BMS can dynamically adjust the power distribution. For example, when the system predicts that the component will enter a state of accelerated degradation, the current density of the FCV will be decreased and the additional power consumption will be shared by the battery in a larger proportion. At the same time, the transient load variation, e.g., the oscillation during acceleration or regenerative braking, should be smoothed out to alleviate the mechanical and chemical stress of the fuel cell and improve its service life.

Secondly, more adaptable operation and longer service life under real driving conditions should be achieved. It is obvious that FCVs will run in various conditions affected by weather, road gradient, SOC, and driving behavior. By accepting multi-source information, the BMS can adopt more advanced control algorithms, such as fuzzy logic or model predictive control (MPC), and adjust the related operation parameters automatically. For example, when the humidity is high, the BMS can control the fuel cell to increase the airflow to prevent the occurrence of electrode flooding;

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when the vehicle is stuck in the traffic congestion, the BMS can suppress the start–stop cycles of the fuel cell to alleviate its degradation. This solution entails adding data-driven learning of operating strategies to the BMS. Based on historical data and real-time data from vehicle operation, machine learning (ML) and prognostic health management (PHM) can predict the RUL of key components. A combination of short-range predictive models (e.g., state estimation) and long-range degradation models can lead to more accurate forecasting and more opportunities for proactive maintenance and energy management. For an fleet, the vehicles' data can be uploaded to the cloud for aggregated analysis to find the best operating strategies for all vehicles. The cloud then sends this information back to the BMS over the air. This learning from the fleet can be beneficial for the entire system. This solution addresses better integration and communication between subsystems. The BMS should be the center of an integrated energy management platform. Fuel cells, batteries, power converters, and thermal management should communicate with the BMS through high-speed communication protocols such as CAN FD or automotive Ethernet. This would enable the vehicles to respond as a coordinated whole—say, by adjusting coolant pump speed to match current output—when high power is demanded. An integrated architecture would also enable a tight relationship between faults and diagnoses and would facilitate reconfiguration of the system if a fault occurs.

In terms of optimization schemes, several avenues are pertinent. In the first scheme, advanced control algorithms are adopted. Going beyond the traditional thermostat and power-following strategies, fuzzy logic and MPC are capable of predictive and adaptive control. Recently, new improved sparrow search algorithms in metaheuristic optimization have been introduced to auto-tune fuzzy membership functions and control parameters, which will improve decision making accuracy in fuzzy logic control of VCPs under uncertain conditions. The second scheme is to replace sensors and data acquisition cards. With the aid of high accuracy sensors, slight voltage, current, and temperature variations can be well measured and a reliable and safe BMS can be implemented. In addition, Kalman and particle filters can be implemented to suppress noises and other disturbances on signals. By applying edge computing modules to process data locally, the system can reduce the latency of the critical control loops and also relieve the communication loads of the central processors. The third scheme is thermal–electrical co-management. Temperature has a great impact on the performance and lifetime of fuel cells and batteries. By implementing joint thermal management strategies, such as pre-cooling the stack before the arrival of high load profiles or coordinated heating during cold starts, the impacts of degradation can be reduced and the efficiency can be improved. By applying forecast-based strategies, if navigation and traffic data indicate upcoming heavy loads or if thermal loads can be predicted using traffic data, the system can implement thermal adjustment in advance.

In summary, by implementing degradation-aware control strategies, adaptive algorithms, learned learning strategies, and deeply integrated hardware/software platforms, BMS can evolve from static controllers to intelligent, adaptive, and scalable energy management controllers. These improvements are essential to the performance and lifetime of FCVs and will promote the development of hydrogen mobility.

5. Conclusion

This study has comprehensively examined the pros and cons of current BMSs for FCEVs in hydrogen. These systems have shown capability in basic energy allocation, multi-subsystem coordination, and fault diagnosis in meeting required operation under typical driving cycles. However, they show significant limitations in accounting for long-term gradual component degradation, operating in complicated real-world environments, utilizing operation information for

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lifelong optimization, and achieving seamless integration across systems. These limitations significantly impact the durability, economy, and scalability of FCEVs under real-world operation.

To address these challenges, this paper proposes several advances to achieve long-term degradation adaptation, real-time parameter tuning with environmental and operation information, embedded machine learning for prognostic health feedback, and unified platform integration with fast vehicle area networks. These advances are designed to work in synergy—enabling FCEVs to be aware of future degradation, respond to varying conditions, learn from the fleet operation, and achieve coordinated control across systems. Several further advances in algorithm tuning, sensing accuracy, and thermal-electrical co-management will support these basic strategies and build a comprehensive framework for next-generation BMSs based on intelligent, connected, and adaptive energy management systems.

Moving beyond traditional BMSs toward intelligent, connected, and adaptive energy management systems is necessary to bridge the gap between lab and real-world vehicle operation. By improving predictive accuracy, operational flexibility, and system interoperability, the proposed approaches have great potential to improve service life, reduce lifecycle cost, and increase consumer confidence in hydrogen mobility. However, these advances still need to be evaluated under real-world conditions. Future work should focus on developing efficient real-time algorithms, performing large-scale pilot studies with commercial fleets, and establishing secure data sharing to support continuous optimization across the vehicle system. Only with a more resilient and intelligent BMS will FCEVs achieve commercial success, which in turn will become an enabling technology for sustainable transportation.

References

[1] Zhou, D.M., Wu, Y.M., Gao, F., Breaz, E., Ravey, A. and Miraoui, A. (2017) Degradation prediction of PEM fuel cell stack based on multiphysical aging model with particle filter approach. IEEE Transactions on Industry Applications, 53, 4041-4052.

[2] Hu, Y., Zhang, L., Jiang, Y., Peng, K. and Jin, Z. (2023) A hybrid method for performance degradation probability prediction of proton exchange membrane fuel cell. Membranes, 13, 426.

[3] Zheng, Z., Morando, S., Péra, M.-C., Hissel, D., Larger, L., Martinenghi, R. and Baylon Fuentes, A. (2017) Brain-inspired computational paradigm dedicated to fault diagnosis of PEM fuel cell stack. International Journal of Hydrogen Energy, 42, 5410-5425.

[4] Zhang, Z., Wang, Y.-X., He, H. and Sun, F. (2021) A short- and long-term prognostic associating with remaining useful life estimation for proton exchange membrane fuel cell. Applied Energy, 304, 117841.

[5] Cheng, Y., Zerhouni, N. and Lu, C. (2018) A hybrid remaining useful life prognostic method for proton exchange membrane fuel cell. International Journal of Hydrogen Energy, 43, 12314-12327.

[6] Li, J., Yang, L., Yang, Q., Wei, Z., He, Y. and Lan, H. (2022) Degradation adaptive energy management with a recognition-prediction method and lifetime competition-cooperation control for fuel cell hybrid bus. Energy Conversion and Management, 271, 116306.

[7] Liu, H., Chen, J., Hissel, D. and Su, H. (2019) Remaining useful life estimation for proton exchange membrane fuel cells using a hybrid method. Applied Energy, 237, 910-919.

[8] Lu, F., Wang, Y., Huang, J., Huang, Y. and Qiu, X. (2018) Fusing unscented Kalman filter for performance monitoring and fault accommodation in gas turbine. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 232, 556-570.

[9] Xie, R., Ma, R., Pu, S., Xu, L., Zhao, D. and Huangfu, Y. (2020) Prognostic for fuel cell based on particle filter and recurrent neural network fusion structure. Energy AI, 2, 100017.

[10] Hassan, Q., Azzawi, I.D., Sameen, A.Z. and Salman, H.M. (2023) Hydrogen fuel cell vehicles: Opportunities and challenges. Sustainability, 15, 11501.