

PEMFC-Based Hybrid Electric Vehicles a Comprehensive Review of Power Management, Challenges, and Optimization Strategies

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Abstract

The increasing demand for sustainable transportation has accelerated research into fuel-cell-based hybrid electric vehicles (FC-HEVs), particularly those powered by proton exchange membrane fuel cells (PEMFCs). PEMFCs offer high energy conversion efficiency, low operating temperature, rapid start-up capability, and zero tailpipe emissions, making them a promising alternative to conventional internal combustion engine powertrains. However, the intermittent nature of vehicle load demand, limited dynamic response of PEMFCs, degradation under transient operating conditions, and high system cost present significant challenges to their widespread adoption. Hybridization of PEMFCs with secondary energy storage systems, such as lithium-ion batteries, supercapacitors, or battery–supercapacitor combinations, provides an effective approach for improving vehicle performance, energy efficiency, durability, and regenerative braking capability. This paper provides a comprehensive assessment of PEMFC-based hybrid electric vehicle architectures, focusing on power management, energy management strategies, system-level challenges, and optimization techniques. Different hybrid powertrain configurations, including passive, semi-active, and fully active topologies, are examined with respect to power-flow control, component utilization, efficiency, and dynamic performance. Particular attention is given to optimization methods employed to minimize hydrogen consumption, battery degradation, fuel-cell degradation, and overall operating cost while maintaining required vehicle performance.

Keywords: Proton Exchange Membrane Fuel Cell (PEMFC), Hybrid Electric Vehicles (HEVs), Fuel Cell Hybrid Electric Vehicles (FC-HEVs), Energy Management System (EMS); Power Management Systems, Intelligent Energy Management.

1. Introduction

The increasing demand for sustainable transportation has accelerated research into electric propulsion technologies that can reduce dependence on petroleum-derived fuels and mitigate local air pollution. Battery electric vehicles (BEVs), hybrid electric vehicles, and fuel-cell electric vehicles (FCEVs) represent different pathways toward transport electrification. Among these options, PEMFC-based hybrid electric vehicles are particularly attractive for applications requiring extended driving range, rapid refuelling, and sustained power delivery. A PEMFC converts the

chemical energy of hydrogen and oxygen into electrical energy through electrochemical reactions. When hydrogen is produced using low-carbon energy and supplied through an appropriately designed infrastructure, the technology can contribute to reduced lifecycle greenhouse-gas emissions. At the vehicle tailpipe, the principal reaction product is water. Nevertheless, the overall environmental benefit depends on hydrogen production, compression, transportation, storage, and distribution. A standalone fuel-cell powertrain faces difficulties when the traction motor demands rapid

power changes. Fuel-cell systems have electrochemical, air-supply, humidification, and thermal-management dynamics that limit their ability to follow abrupt load variations efficiently. Repeated operation under unfavourable conditions may also accelerate degradation. Hybridization with a battery or supercapacitor helps separate the relatively slow energy-generation process from fast traction-power demands. The energy management system (EMS) is responsible for distributing the required power among the available sources while respecting their operating constraints. Its decisions affect hydrogen consumption, fuel-cell efficiency, battery state of charge (SOC), component ageing, regenerative braking recovery, and vehicle drivability. Consequently, the EMS is a central element in determining the practical efficiency and durability of a PEMFC-based HEV. Earlier research has examined hybrid power-system architectures, optimization-based energy management, component sizing, and health-aware control. More recent work investigates predictive control, intelligent learning-based methods, and connected vehicle operation [1] – [5]. Despite this progress, a significant challenge remains: strategies that perform well in a simulation or over a known driving cycle may not achieve the same results under uncertain traffic, changing component health, temperature variation, and real-time computational limitations.

2. Literature Review

2.1. Hybrid Power System Design for PEMFC-based HEVs

Researchers reviewed hybrid power system configurations combining PEM fuel cells with batteries and supercapacitors. The study compared energy management strategies and highlighted limitations in dynamic response, system efficiency, and fuel cell lifetime. The review established the importance of selecting suitable hybrid architectures and control strategies to improve vehicle performance.

2.2. Optimization of Energy Management Systems

Sulaiman et al. examined optimization techniques for fuel-cell hybrid electric vehicles. Their work discussed the allocation of power between fuel cells

and auxiliary energy storage devices to reduce hydrogen consumption and improve system performance. The study emphasized the need to balance energy efficiency, operating cost, and component durability.

2.3. Driving-Cycle-Based Energy Management

The review Review of Energy Management Methods for Fuel Cell Vehicles: From the Perspective of Driving Cycle Information investigated how driving-cycle information can support energy management decisions. Its findings highlight the importance of predicting vehicle power demand to improve fuel-cell operation and energy utilization under varying driving conditions.

2.4. Optimal Sizing and Power Management Of Hybrid Energy Sources

Mohammed et al. reviewed fuel cell–battery–supercapacitor hybrid systems, focusing on optimal component sizing, power distribution, predictive energy management, and hybrid optimization algorithms. The study showed that energy storage sizing and energy management should be considered together to improve efficiency, minimize energy losses, and limit battery and fuel-cell degradation.

2.5. Advanced control strategies for FCHEVs

The review Advanced Control Strategies for Fuel Cell Hybrid Electric Vehicles examined control algorithms, hybrid energy configurations, and emerging optimization methods. It provides a useful foundation for studying advanced control techniques, including learning-based methods, to improve power sharing and system response.

2.6. Intelligent Energy Management and Future Research Directions

A recent review in Next Energy examined hybrid energy system topologies and energy management strategies for fuel-cell-based vehicles. It discussed rule-based, optimization-based, and learning-based methods, along with challenges involving durability, safety, real-time control, and system scalability.

2.7. Comprehensive Energy Management Review

Kumar and Bhattacharjee reviewed energy management strategies for fuel-cell-based electric vehicles, including hybrid energy sources and their integration with vehicle powertrains. Their work

identified the need for more intelligent and reliable energy management methods to improve fuel efficiency and extend the operating life of hybrid power systems [6 - 10].

3. Methodology

3.1. Operating Principle of PEMFCs

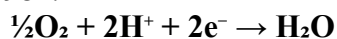
A PEMFC uses a polymer electrolyte membrane to conduct protons between the anode and cathode while restricting direct electron transport. Hydrogen supplied to the anode undergoes oxidation, releasing protons and electrons. The protons pass through the membrane, while electrons travel through an external electrical circuit and provide useful power. At the cathode, oxygen reacts with the protons and electrons to form water. Shown in Figure 1.

The principal reactions are:

Anode reaction:



Cathode reaction:



Overall reaction:

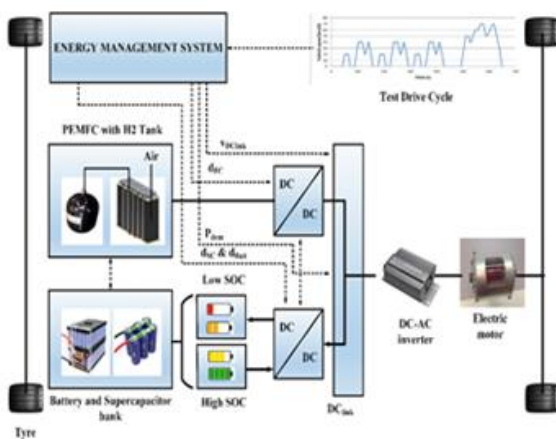


Figure 1 Schematic Representation of a Hybrid PEM Fuel Cell, Battery, and Supercapacitor Energy Management System for Electric Vehicle Applications

A single cell produces a relatively low voltage, so multiple cells are connected in series to form a stack suitable for vehicle applications. The stack is integrated with auxiliary subsystems, including hydrogen delivery, air compression, cooling, water management, sensors, and control electronics. The

net electrical power is lower than the gross stack output because auxiliary equipment consumes power. Therefore, an EMS should consider net system efficiency rather than relying exclusively on stack-level performance.

3.2. Power Management and Energy Management Strategies

Rule-based strategies use predetermined conditions to determine power allocation. These strategies include thermostat control, state-machine control, and fuzzy logic. For example, the fuel cell may supply the average propulsion demand, while the battery provides additional power during acceleration. During braking, regenerative energy is directed to the battery or supercapacitor when charging constraints permit. Rule-based methods are computationally inexpensive and relatively easy to implement in embedded controllers. They are particularly useful when transparent control decisions and predictable behaviour are important. However, their performance depends on the selection of thresholds and calibration parameters. Fixed rules may not adapt effectively to changes in driving patterns, ambient temperature, component ageing, or vehicle load. Fuzzy logic can improve adaptability by representing operating conditions through linguistic rules, but its membership functions and rule base still require careful design.

4. Hybrid Energy Storage and Component Sizing

4.1. Battery Integration

The battery supports transient loads, stores regenerative braking energy, and can supply propulsion power when fuel-cell output is limited. Its performance depends on SOC, temperature, current, ageing, and charging constraints. Repeated high-current operation and deep cycling can accelerate degradation. Accordingly, the EMS should avoid treating the battery as an unlimited energy source. Battery SOC must be maintained within specified operating limits, and the final SOC should be considered when comparing energy consumption across drive cycles [11] & [12].

4.2. Supercapacitor Integration

Supercapacitors can deliver high power over short intervals and accept regenerative energy rapidly.

Their integration can reduce battery peak-current demands and help buffer sudden traction loads. However, their relatively low energy density, additional cost, mass, and conversion losses must be considered. Their usefulness depends on the frequency and magnitude of transient loads and the effectiveness of the power-splitting controller Shown in Figure 2.

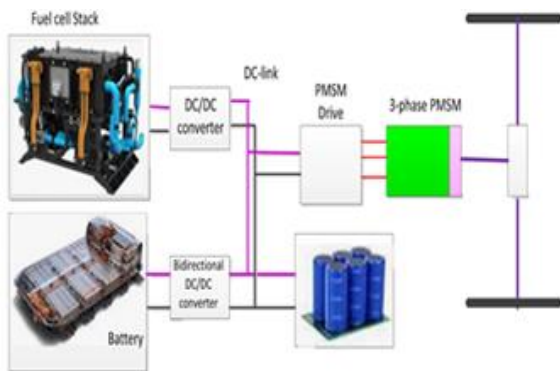


Figure 2 Schematic Diagram of a Fuel Cell–Battery Hybrid Electric Vehicle Powertrain Integrated with Bidirectional DC/DC Converters and a Permanent Magnet Synchronous Motor (PMSM)

4.3. Hybrid Storage Coordination

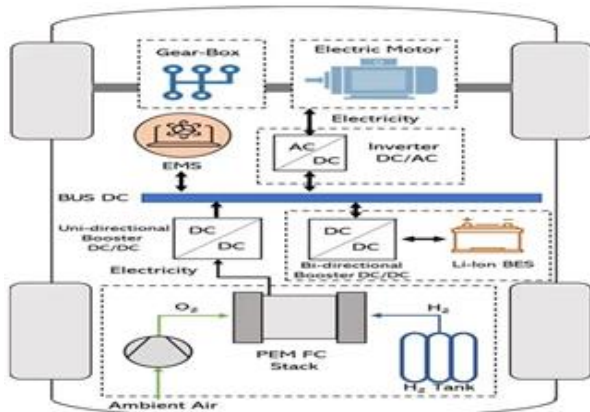


Figure 3 Schematic Representation of a PEM Fuel Cell–Battery Hybrid Electric Vehicle Powertrain with Integrated Energy Management System and DC/DC Power Converters

In a fuel-cell–battery–supercapacitor architecture, a possible control principle is to assign average power to the fuel cell, intermediate-duration power

variations to the battery, and short-duration high-frequency variations to the supercapacitor. This principle is not universally optimal. The actual power split depends on component efficiencies, state constraints, driving conditions, and the energy-management objective. Frequency-based power allocation can be combined with optimization to determine suitable filtering parameters and component sizes. However, filtering alone does not guarantee minimum hydrogen consumption or maximum lifetime. A supervisory controller must correct for SOC drift and account for conversion losses and component limitations Shown in Figure 3.

4.4. Optimal Component Sizing

The fuel-cell rated power, battery capacity, supercapacitor size, and hydrogen storage capacity influence vehicle mass, cost, acceleration, range, and efficiency. An oversized fuel cell increases cost and may operate inefficiently at low loads. An undersized fuel cell can cause excessive battery cycling and restrict sustained performance. Similarly, insufficient battery capacity may increase fuel-cell transients, whereas excessive battery capacity increases vehicle mass and material requirements. Component sizing and EMS design should therefore be treated as a coupled optimization problem. A suitable design framework evaluates vehicle performance, energy consumption, durability, and total cost of ownership under representative driving cycles [1], [2].

Conclusion

PEMFC-based hybrid electric vehicles offer a promising route toward low-tailpipe-emission transportation by combining hydrogen fuel cells with electrical energy storage. Their practical performance, however, depends strongly on the coordination of the fuel-cell stack, battery, optional supercapacitor, power converters, and traction motor. This review examined the principal powertrain architectures and energy management approaches, including rule-based control, ECMS, dynamic programming, MPC, metaheuristic optimization, and reinforcement learning. Each approach presents different trade-offs between implementation complexity, predictive capability, computational burden, and adaptability. A major conclusion is that hydrogen consumption should not be optimized in

isolation. Fuel-cell durability, battery ageing, transient response, safety, component sizing, and lifecycle cost must also be considered. Predictive, adaptive, and health-aware strategies offer promising opportunities, but their benefits must be demonstrated under consistent benchmarking conditions and realistic operating constraints.

Future Scope

Future research should prioritize integrated component sizing and control, robust degradation-aware optimization, transparent evaluation, and hardware-level validation. Progress in these areas will be important for improving the efficiency, reliability, economic viability, and wider adoption of PEMFC-based hybrid vehicles.

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