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COMPARATIVE ANALYSIS OF ENERGY MANAGEMENT SYSTEM (EMS) COMPONENTS IN BATTERY ELECTRIC VEHICLES AND HYDROGEN FUEL CELL ELECTRIC VEHICLES

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Abstract. In electric vehicles, energy management systems (EMS) are essential for enhancing performance, extending lifespan, improving efficiency, and ensuring safety. The design and control requirements for EMS differ significantly between hydrogen fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs). This distinction arises because FCEVs combine fuel cell stacks with supplementary energy storage components, while BEVs depend exclusively on electrochemical energy storage systems. The functional blocks, supervisory control techniques, component-level coordination, and system-level optimization issues of the EMS components in BEVs and FCEVs are compared in an organized manner in this paper. While FCEV EMS must manage multi-source hybrid energy systems incorporating hydrogen, fuel cell dynamics, and balance-of-plant subsystems, BEV EMS is mostly battery-centric, according to the research. System complexity, control goals, and potential future research areas in advanced energy management techniques are all clarified by the comparison.

Keywords: BEVs, FCEVs, EMS, battery management system, fuel cell system, battery degradation, fuel cell durability

Аннотация. В электромобилях системы управления энергией (СУЗ) играют важнейшую роль в максимизации производительности, долговечности, эффективности и безопасности. Конструкции СУЗ и потребности в управлении водородными электромобилями (ВЭБ) и электромобилями с аккумуляторными батареями (ЭБ) значительно различаются, поскольку ВЭБ сочетают топливные элементы с вспомогательными накопителями энергии, в то время как ЭБ используют только электрохимические системы хранения энергии. В данной статье систематически сравниваются функциональные блоки, методы диспетчерского управления, координация на уровне компонентов и вопросы оптимизации на системном уровне компонентов СУЗ в ЭБ и ВЭБ. Согласно исследованию, СУЗ ВЭБ должна управлять

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многоисточниковыми гибридными энергетическими системами, включающими водород, динамику топливных элементов и подсистемы вспомогательного оборудования, тогда как СУЗ ЭБ в основном ориентирована на батареи. Сравнение проясняет сложность системы, цели управления и потенциальные направления будущих исследований в области передовых методов управления энергией.

Ключевые слова: электромобили, автомобили на топливных элементах, система управления энергией, система управления батареей, система топливных элементов, деградация батареи, долговечность топливного элемента

Annotatsiya. Elektr transport vositalarida energiyani boshqarish tizimlari (EMS) ishlash, chidamlilik, samaradorlik va xavfsizlikni maksimal darajada oshirishda muhim rol o'ynaydi. Vodorodli elektr transport vositalari (FCEVs) va akkumulyatorli elektr transport vositalarining (BEVs) EMS dizayni va nazorat qilish ehtiyojlari sezilarli darajada farq qiladi, chunki FCEV'lar yoqilg'i xujayralarini yordamchi energiya saqlash qurilmalari bilan birlashtiradi, BEV'lar esa faqat elektrokimyoviy energiya saqlash tizimlaridan foydalanadi. Ushbu maqola funktsional birliklarni, nazoratni boshqarish usullarini, komponentlar darajasida muvofiqlashtirishni va FCEV va FCEV'larda EMS komponentlarini tizim darajasida optimallashtirish masalalarini muntazam ravishda taqqoslaydi. Tadqiqotga ko'ra, FCEV boshqaruv tizimi ko'p manbali gibrid energiya tizimlarini, jumladan vodorod, yonilg'i xujayrasi dinamikasi va yordamchi uskunalar quyi tizimlarini boshqarishi kerak, elektr mobillar boshqaruv tizimi esa birinchi navbatda batareyalarga qaratilgan. Taqqoslash tizimning murakkabligini, boshqaruv maqsadlarini va energiyani boshqarishning ilg'or usullari sohasida kelajakdagi tadqiqot yo'nalishlarini aniqlaydi.

Kalit so'zlar: elektr transport vositalari, yonilg'i xujayrasi transport vositalari, energiyani boshqarish tizimi, batareyani boshqarish tizimi, yonilg'i xujayrasi tizimi, batareyaning buzilishi, yonilg'i xujayrasi chidamliligi.

INTRODUCTION

The global transition toward low-carbon transportation has accelerated the development of electrified vehicle technologies. Increasing concerns over greenhouse gas emissions, urban air pollution, and fossil fuel dependency have positioned electric propulsion systems as a cornerstone of sustainable mobility strategies. Among zero-emission technologies, **Battery Electric Vehicles (BEVs)** and **Hydrogen Fuel Cell Electric Vehicles (FCEVs)** have emerged as the most promising alternatives to conventional internal combustion engine vehicles. Although both architectures utilize electric traction motors and high-voltage power

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electronics, they differ fundamentally in energy sourcing, storage, and conversion mechanisms. BEVs store electrical energy directly in high-capacity lithium-ion battery packs, while FCEVs generate electricity onboard through hydrogen electrochemical conversion in a fuel cell stack, typically supported by a secondary battery or supercapacitor for transient power buffering. These architectural differences significantly influence the design philosophy and complexity of the Energy Management System (EMS). An EMS serves as the supervisory control layer responsible for coordinating energy flow between sources, storage elements, and propulsion components. It ensures that driver torque demand is satisfied while respecting operational constraints such as voltage, current, temperature, and durability limits. In addition, EMS algorithms aim to optimize energy efficiency, extend component lifetime, and maintain safety compliance. From a systems engineering perspective, EMS design must address multi-domain interactions involving:

- Electrical energy flow (DC bus regulation, inverter control)
- Electrochemical storage behavior (battery SOC, degradation)
- Hydrogen-to-electric conversion dynamics (in FCEVs)
- Thermal subsystems
- Auxiliary loads
- Safety-critical monitoring

In BEVs, EMS architecture is largely storage centric. Since the battery is the sole energy reservoir, the main control challenge lies in balancing efficiency, power capability, and long-term battery health. Advanced battery management algorithms for state estimation (SOC, SOH, SOP) and degradation-aware control are therefore central to BEV EMS design.

In contrast, FCEVs present a hybrid energy generation problem. The fuel cell stack operates most efficiently within specific load regions and exhibits slower transient response compared to batteries. Therefore, the EMS must coordinate power split between the fuel cell and the auxiliary battery while also accounting for balance-of-plant (BoP) subsystems such as air compressors, humidification units, and cooling circuits. These additional subsystems introduce parasitic power consumption and further complexity in optimization.

The distinction between BEV and FCEV EMS becomes even more pronounced in heavy-duty applications, where vehicles operate under high load variability, long driving cycles, and stringent durability requirements. In such cases, the EMS must consider not only instantaneous efficiency but also lifecycle optimization metrics such as hydrogen consumption per kilometer, battery cycling intensity, and fuel cell voltage degradation rate.

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Recent research trends have moved beyond rule-based energy management toward advanced optimization strategies, including:

- Equivalent Consumption Minimization Strategy (ECMS)
- Model Predictive Control (MPC)
- Stochastic dynamic programming
- Reinforcement learning-based energy management

These methods aim to address multi-objective trade-offs between efficiency, durability, safety, and system reliability in real-time.

Given the increasing prevalence of electric vehicles in both personal and commercial sectors, it is essential to perform a comprehensive analysis of the energy management system (EMS) frameworks employed in battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). Examining their architectural differences, operational challenges, and control issues provides valuable insights for enhancing powertrain development, particularly regarding emerging hydrogen-fueled heavy-duty transportation options.

This paper aims to provide a structured analysis of EMS components in BEVs and FCEVs, highlighting similarities, differences, and implications for advanced control strategy design.

1. EMS IN BATTERY ELECTRIC VEHICLES (BEVS)

In BEVs, the high-voltage battery pack is the sole onboard energy source, making battery monitoring, protection, and optimization the central focus of EMS design.

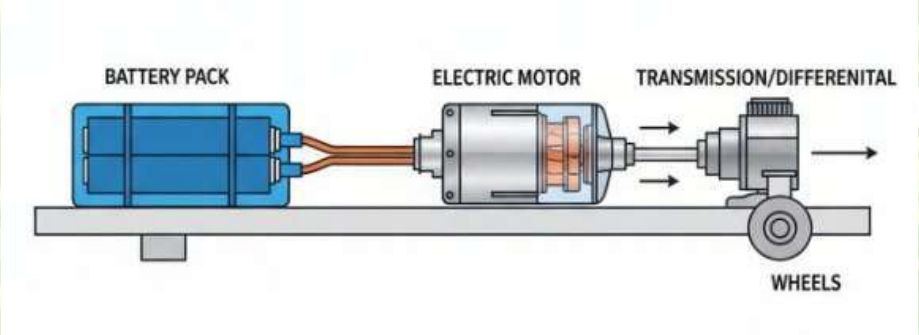


Figure 1: the powertrain of battery electric vehicles

Main components of EMS

- **Battery Management System (BMS):** Monitors cell voltages, state of charge (SOC), temperature, and implements cell balancing.
- **Motor/Inverter Coordination:** Supervises torque requests, efficiency optimization, and thermal constraints.
- **Regenerative Braking Controller:** Allocates braking torque between regeneration and friction brakes.

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• **Thermal Management:** Maintains temperature within optimal bounds for efficiency and aging minimization.

• **Charging Energy Management:** Controls charge current profiles to balance fast charge capability with battery health.

Control Objective: Maximize driving range and efficiency while minimizing battery degradation.

In summary, BEV EMS architecture is:

• Storage-driven

• Electrically dominant (single energy source)

• Focused on battery protection and efficiency

• Moderately complex compared to hybrid systems

Although structurally simpler than FCEV systems, BEV EMS requires high accuracy in state estimation and strict safety management due to the central role of the battery. The performance, range, and lifetime of the vehicle are directly dependent on the quality of the EMS design.

2. EMS IN HYDROGEN FUEL CELL ELECTRIC VEHICLES (FCEVS)

As described in figure 2, FCEVs include hydrogen storage, a fuel cell stack, DC/DC converters, a buffer battery, and electric propulsion systems. EMS must coordinate energy delivery between hydrogen conversion and battery buffer systems.

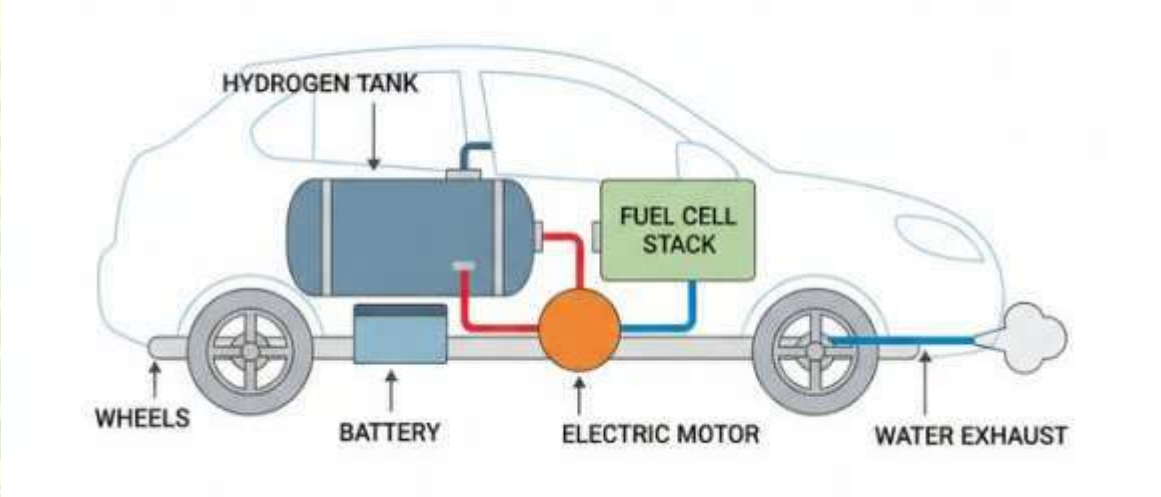


Figure 2: Powertrain of FCEV

2.1 MAIN COMPONENTS OF EMS IN FCEV:

• **Fuel Cell System Controller:** Sets fuel cell power targets, manages stack operation, and protects against transient overloads.

• **Balance-of-Plant (BoP) Coordination:** Includes air compressors, humidifiers, and cooling, all of which consume parasitic power and affect net efficiency.

• **Hybrid Power Split Controller:** Determines how load is shared between the fuel cell and battery.

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• **Hydrogen Safety Supervision:** Monitors tank pressure, leakage detection, and activation of safety shutdown mechanisms.

Control Objective: Minimize hydrogen consumption while preserving fuel cell durability and efficiently using battery storage.

3. Comparison of EMS components

Table 1:

Comparative analysis of EMS compartments of BEV and FCEV

Feature	BEV's EMS	FCEV's EMS
Primary energy source	battery only	Hydrogen + battery
System complexity	Moderate	High
Fast transient handling	Battery inherently fast	Battery buffers for slower fuel cell response
Dominant constraints	Battery limits	Battery buffers for slower fuel cell response
Efficiency focus	Maximize electrical energy use	Minimize hydrogen use and parasitic losses
Additional systems	Thermal and charging	BoP, pressure systems, hybrid power split

Table 1, presents a structured comparison between the Energy Management Systems (EMS) of Battery Electric Vehicles (BEVs) and Hydrogen Fuel Cell Electric Vehicles (FCEVs), highlighting their architectural differences, control priorities, and system complexity.

The comparison shows that BEV EMS is fundamentally **battery-centered**, focusing on optimizing electrical energy usage while protecting battery health and ensuring safe operation. Since the battery is the sole energy source, the supervisory control structure is relatively straightforward, mainly managing torque allocation, regenerative braking, thermal regulation, and charging control.

In contrast, FCEV EMS is **hybrid and multi-source oriented**, requiring coordination between the fuel cell stack and the auxiliary battery. The supervisory controller must determine optimal power split while considering fuel cell efficiency regions, dynamic response limitations, hydrogen consumption, and balance-of-plant (BoP) parasitic loads. This makes FCEV EMS inherently more complex than BEV EMS.

Furthermore, although Battery Electric Vehicles (BEVs) focus mainly on issues related to battery longevity and energy efficiency, Fuel Cell Electric Vehicles (FCEVs) need to concurrently handle challenges associated with fuel cell lifespan, hydrogen safety regulations, and the impacts of battery cycling. The section concludes that FCEV energy management demands more advanced

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optimization strategies due to its multi-domain control requirements and hybrid energy interactions.

4. System Complexity and Control Challenges

4.1 BEV Challenges

- Accurate SOC and state of health estimation.
- Thermal management during fast charging.
- Maximizing regenerative braking.

4.2 FCEV Challenges

- Managing slower fuel cell response through buffer storage.
- Including BoP parasitic loads in optimization.
- Ensuring safe hydrogen handling and reducing degradation under variable load conditions.

In conclusion, while both BEV and FCEV Energy Management Systems face significant control challenges, the nature of these challenges differs substantially. BEV EMS complexity is primarily driven by battery protection, accurate state estimation, thermal management, and efficient regenerative braking. The system focuses on optimizing a single energy source under strict electrochemical constraints.

In contrast, FCEV EMS involves a higher level of complexity due to its hybrid architecture. It must coordinate fuel cell dynamics, battery buffering, balance-of-plant parasitic loads, and hydrogen safety constraints simultaneously. The slower transient response of fuel cells and durability considerations further increase the need for advanced supervisory control strategies.

Overall, FCEV energy management requires more comprehensive and multi-objective optimization frameworks compared to BEVs, making it a more demanding control problem from both modeling and real-time implementation perspectives.

The hybrid architecture of FCEVs demands more expansive optimization strategies than in BEVs because fuel cell dynamics and auxiliary systems introduce additional operational constraints.

5. DISCUSSION

EMS design fundamentally reflects the underlying energy architecture of the vehicle. In BEVs, the presence of a single dominant energy source — the battery — simplifies the supervisory control problem from a structural standpoint. The EMS primarily regulates power flow between the battery and traction motor while ensuring voltage stability, thermal safety, and battery longevity. Although advanced estimation and protection algorithms are required, the energy flow path remains relatively linear and electrically confined. Consequently, optimization

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objectives are typically centered around maximizing driving range, minimizing battery degradation, and improving regenerative braking efficiency.

However, in FCEVs, EMS design becomes a multi-domain control challenge. Unlike BEVs, FCEVs combine electrochemical energy conversion (hydrogen to electricity) with electrochemical energy storage (battery). The fuel cell stack exhibits slower dynamic response compared to batteries and operates most efficiently within a limited power range. Rapid load variations caused by acceleration or grade changes must therefore be absorbed by the auxiliary battery or supercapacitor. This hybrid interaction requires the EMS to continuously determine the optimal power split between the fuel cell and battery.

Furthermore, FCEV systems introduce additional constraints not present in BEVs:

- Fuel cell degradation due to load cycling and voltage fluctuations
- Parasitic power consumption from balance-of-plant (BoP) components such as air compressors and cooling systems
- Hydrogen storage pressure and safety limitations
- Startup and shutdown sequencing of the fuel cell stack

These factors transform EMS from a primarily electrical energy optimization problem into a multi-objective control problem involving efficiency, durability, safety, and system reliability.

In heavy-duty and long-range transport applications, the differences become even more pronounced. Heavy-duty vehicles experience high torque demand variability, long operating hours, and stricter durability requirements. For BEVs, this results in challenges such as:

- Large battery sizing
- Thermal management under sustained high loads
- Battery aging due to deep cycling

For FCEVs, heavy-duty usage emphasizes advantages such as fast hydrogen refueling and extended driving range. However, these benefits introduce additional EMS complexity:

- Maintaining fuel cell operation within optimal efficiency regions under fluctuating loads
- Reducing hydrogen consumption per kilometer
- Limiting fuel cell current ripple to prevent premature degradation
- Coordinating high-power transients through battery buffering

Because of these factors, advanced optimization techniques become more relevant in FCEVs. Strategies such as Equivalent Consumption Minimization Strategy (ECMS), Model Predictive Control (MPC), and reinforcement learning-

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based supervisory control are increasingly studied to balance hydrogen efficiency with durability constraints in real time.

6. CONCLUSION

Battery Electric Vehicle (BEV) energy management systems are focused on the goal of battery optimization, and battery protection and range extension. The EMS strategy is mainly aimed at controlling power flow, state of charge within safe operational limits, thermal stress, and degradation effects, as battery used as the only form of onboard energy source. Control strategies in BEVs usually rely on ensuring the optimal power distribution between traction demand and regenerative braking needs while prioritizing the long-term health of the battery and extending driving range. Conversely, the fuel energy management system of Fuel Cell Electric Vehicle (FCEV) must achieve a hybrid energy architecture with a mixture of hydrogen fuel cell module and battery pack. This adds further difficulties, as the EMS should match the fuel cell and its battery in an optimal manner considering fuel cell efficiency, ramp-rate limitations and degradation sensitivity features. Additionally, FCEV systems also include balance-of-plant (BoP) elements—like air compressor, hydrogen circulation system, cooling subsystem and auxiliary loads, which determine the overall system efficiencies. Safety concerns associated with the storage of hydrogen and operation under high pressure further increase supervision requirement. Thus, the EMS design for FCEVs is intrinsically more complex than for BEVs, and it is necessary to develop new supervisory control systems that can be applied to achieve the multi-objective optimization. At the same time, these systems must reduce hydrogen consumption, manage the battery's state of charge, stabilize fluctuations in fuel cell power, and ensure system stability under dynamic driving conditions. Sub-sequent directions for FCEV energy management involve the development of predictive control strategies based on route preview and traffic information, artificial intelligence–based optimization methods for adaptive power split control, and durability-aware energy management strategies that explicitly embrace fuel cell degradation models. All of those are expected to make it more efficient, increase the lives and longevity of components, and ultimately improve the sustainability of hydrogen-powered heavy-duty transportation.

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