
IJERST
International Journal of
Engineering Research and Science & Technology
www.ijerst.org
ISSN : 2319-5991
Vol. 21 No. 3 (1) 2025
ijerst.editor@gmail.com
editor@ijerst.com

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IJERST International Journal of Engineering Research and Science & Technology

ENERGY MANAGEMENT OF BATTERY-PEM FUEL CELL IN HYBRID ELECTRIC VEHICLE

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ABSTRACT

The growing adoption of electric vehicles (EVs) has increased demand for efficient charging infrastructure. This project highlights an energy management of battery-PEM Fuel cell Hybrid energy storage for electric vehicle. The battery alone cannot cater the load demand; it is why fuel cell (FC) is integrated to make the system more sustainable.

The hybrid system is used to produce energy without interruption and it consists of a proton exchange membrane fuel cell (PEMFC) and battery bank storage (BBS) for short-term storage. The mathematical model topology and the energy management of the global system are presented. Obtained results under MATLAB/Simulink and experimental ones obtained and discussed.

Keywords —Proton exchange membrane fuel cell (PEMFC), renewable energy, hydrogen and oxygen fuel. Battery, Energy management, Electric vehicle.

Received: 05-6-2025 Accepted: 08-7-2025 Published: 24-7-2025

1. INTRODUCTION

A fuel cell is an electrochemical cell that converts the chemical energy of a fuel (often hydrogen) and an oxidizing agent (often oxygen) into electricity through a pair of redox reactions. Fuel cells are different from most batteries in requiring a continuous source of fuel and oxygen (usually from air) to sustain the chemical reaction, whereas in a battery the chemical energy usually comes from substances that are already present in the battery. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied. the environment and the fact that photovoltaic has become a mature technology.

Hybrid Electric Vehicles (HEVs) have emerged as a promising solution to reduce fuel consumption and emissions, addressing the growing environmental concerns associated with traditional gasoline-powered vehicles. A key development in this area is the integration of Proton Exchange Membrane (PEM) fuel cells and batteries within HEVs. While batteries are capable of delivering high power for short durations, PEM fuel cells provide a continuous, efficient power source, making them complementary. The challenge, however, lies in managing the energy flow between these two sources to maximize efficiency, minimize fuel consumption, and ensure the longevity of both components.

Energy management strategies play a critical role in optimizing the performance of a battery-PEM fuel cell hybrid system. These strategies control when to draw power from the battery or fuel cell based on real-time driving conditions, such as acceleration, deceleration, and cruising. Efficient energy management can also improve fuel economy, minimize hydrogen consumption, and extend the lifespan of both the battery and the fuel cell.

In order to obtain appreciable output voltages, several fuel cells have to be combined to obtain a fuel cell stack. Most mobile applications and particularly automobiles are dominated by proton exchange membrane fuel cells (PEMFC). This is due to their low operating temperature, so PEMFCs can produce immediately power after start-up. The delivered power can be of a few kW to several hundred kW. A fuel cell works as a battery but it stores energy using hydrogen. It makes hydrogen react with the oxygen in ambient air to obtain water and energy.

In this MATLAB, a powerful simulation tool, is widely used for modeling, simulating, and optimizing energy management systems in HEVs. It provides a comprehensive environment to design and test various control strategies, such as rule-based, optimal control, and state-of-charge (SOC)-based methods. With the help of Simulink and Simscape, MATLAB allows engineers to model the components of a hybrid powertrain, simulate driving cycles, and evaluate the effectiveness of different energy management techniques.

In this study, we explore the energy management of battery-PEM fuel cell hybrid electric vehicles through MATLAB simulations. By evaluating various control strategies, it aims to demonstrate PEM Fuel Cells and Battery storage systems can be used to optimize power distribution, improve efficiency, and ensure the sustainable operation of HEVs. This approach helps researchers and engineers understand how to efficiently manage power distribution in HEVs, focusing on the interaction between the battery, PEM fuel cell, and electric motor

2. SYSTEM CONFIGURATION

The hybrid energy system consists of three main components:

1. **PEM Fuel Cell**: Converts hydrogen into electrical energy.
2. **Battery**: Stores energy and provides a buffer for the fuel cell.
3. **Electric Motor/Drivetrain**: Converts electrical energy into mechanical energy to drive the vehicle.

The fuel cell generates electricity based on the demand from the drivetrain, while the battery supplements the power as necessary, especially during peak power demands or when the fuel cell operates at lower efficiencies. The energy management system plays a crucial role in ensuring that the fuel cell and battery operate in a manner that maximizes the overall system efficiency.

The hybrid energy system in HEVs typically comprises a Proton Exchange Membrane (PEM) fuel cell, a battery, and an electric motor. The PEM fuel cell generates electricity through the electrochemical reaction of hydrogen and oxygen, with water vapor being the only emission. The battery acts as an energy buffer, storing power generated during regenerative braking or excess electricity from the fuel cell. The electric motor converts the stored electrical energy into mechanical power to drive the vehicle's wheels.

The system operates in a way that optimizes both energy usage and efficiency. The fuel cell provides continuous, steady power, especially during cruising, while the battery covers peak power demands, such as during acceleration or high load conditions. The interaction between the fuel cell and battery is managed by an Energy Management System (EMS) that ensures both components operate within their optimal ranges. For instance, the battery's State of Charge (SOC) is maintained within safe limits to prevent damage, and the fuel cell operates efficiently under its best load conditions. An optimal power split is essential for maximizing fuel economy and minimizing operational wear on both the battery and fuel cell.

3. ENERGY MANAGEMENT STRATEGIES

The key objective of energy management in HEVs is to optimize the distribution of power between the fuel cell and the battery. Several approaches to EMS are proposed in the literature, including:

- Rule-based Control: This approach uses predefined rules to determine the power split between the fuel cell and the battery. While simple, it may not always provide optimal performance under varying driving conditions.
- Optimization-based Control: Techniques such as dynamic programming (DP), model predictive control (MPC), and fuzzy logic control (FLC) offer more sophisticated and adaptive strategies. These methods aim to minimize fuel consumption while maximizing the operational efficiency of both the battery and fuel cell.
- Hybrid Control Strategies: These strategies combine multiple techniques,
- such as rule-based control during normal conditions and optimization-based control in more complex scenarios.

Effective energy management in Hybrid Electric Vehicles (HEVs) is critical to achieving optimal performance, fuel efficiency, and emissions reduction. Various energy management strategies (EMS) have been proposed in the literature to control the interaction between the battery and the fuel cell. The simplest approach is rule-based control, where predefined rules determine how power is distributed between the two energy sources based on vehicle load, driving speed, and battery state of charge (SOC). While easy to implement, this method may not always ensure the best performance, especially in dynamic driving conditions. More sophisticated strategies include optimization-based approaches, such as dynamic programming (DP), model predictive control (MPC), and fuzzy logic control (FLC).

These methods are designed to adapt to changing conditions and find the most efficient power split, reducing fuel consumption and extending the vehicle's range. Among these, optimization techniques like DP and MPC can account for future driving events and minimize energy losses. Hybrid control strategies, which combine rule-based and optimization-based methods, are also gaining attention as they offer both simplicity and adaptability. This paper focuses on an optimization-based EMS that dynamically adjusts the power split between the fuel cell and battery to achieve the best performance under varying driving conditions.

4. METHODOLOGY

Fig. 1: Block diagram of PEM Fuel Cells-Battery HEV

The methodology for modeling a Battery-PEM Fuel Cell Hybrid Electric Vehicle (HEV) follows a structured approach, which is divided into the following steps:

Step 1: Research Problem The primary research problem addressed by this methodology is the need to reduce dependence on fossil fuels for energy generation, which leads to issues such as:

▪ Environmental Pollution: Fossil fuel-based energy generation produces harmful emissions that contribute to climate change.

▪ Efficiency: Conventional internal combustion engines and energy generation methods are inefficient and have higher energy losses.

▪ Sustainability: A growing concern for reducing carbon emissions and finding sustainable energy alternatives.

▪ Dependence on Finite Resources: Fossil fuels are finite resources, leading to concerns about energy supply reliability.

Proposed Solution: The research proposes using a Battery-PEM Fuel Cell Hybrid System for Hybrid Electric Vehicles. The fuel cell provides a clean, renewable energy source by using hydrogen, while the battery offers fast energy delivery and recovery during high-demand situations like acceleration.

The combination of these two technologies addresses efficiency, environmental, and sustainability concerns in modern transportation.

Step 2: Methods of Data Collection

▪ Secondary Data Collection: Data is gathered from previous research, peer-reviewed articles, and studies related to PEM fuel cell technology, hybrid vehicles, energy management systems, and renewable energy solutions. This data includes information about the behavior of PEM fuel cells, battery characteristics, power management strategies, and hybrid system optimization techniques.

▪ Tools: The primary tool used for simulation and modeling is MATLAB/Simulink. MATLAB/Simulink is used for building accurate mathematical models of the PEM fuel cell, battery, motor, and energy management system, as well as simulating the interaction of these components under various driving conditions.

Step 3: Method of Analysis The analysis focuses on the operation and behaviour of the PEM Fuel Cell and its integration with the battery in a hybrid vehicle setup. The PEM fuel cell works through the following electrochemical reactions:

Anode Reaction:

$$2H_2 \rightarrow 4H^+ + 4e^-$$

Cathode Reaction:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

Total Cell Reaction:

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Electricity} + \text{Heat}$$

Step 4: Evaluation & Justification Features of the PEM Fuel Cell:

▪ High Efficiency: The PEM fuel cell has a higher energy conversion efficiency than conventional combustion engines. This is essential for reducing fuel consumption and extending the range of the hybrid vehicle.

▪ Environmental Benefits: The fuel cell produces zero emissions, contributing to cleaner air and reduced environmental impact. The only byproducts are water and heat.

▪ Continuous Power Generation: Unlike batteries, which can discharge over time, the PEM fuel cell can provide continuous power, enhancing the vehicle's driving range and performance.

4.1. MODES OF OPERATION

Mode-1: If the load power is inferior to the Fuel Cell power, the latter ensures the power supply of electric motor and charges Battery, if it is higher than Fuel Cell, Battery ensure the power supply of Electric motor.

Mode-2: The vehicle is in braking mode if the variation in the load power is negative. In this case, the power supplied by Fuel Cell is used to charge Battery in the case of discharge.

Mode-3: The stopping mode involves two cases: in the first one, the power required by the electric engine of traction and the total one provided by Fuel Cell and the storage element are considered zero. The second case appears when there is available power in Fuel Cell used to charge Battery.
These modes of operation (Mode 1, Mode 2, and Mode 3) ensure that the Battery-PEM Fuel Cell Hybrid Electric Vehicle operates efficiently in various conditions. By dynamically managing power from both the Fuel Cell and Battery, the system enhances the overall vehicle performance, maximizes energy recovery during braking, and ensures that energy is stored effectively when not in use. This intelligent management improves fuel economy, extends driving range, and reduces environmental impact.

5. SIMULATION AND RESULT

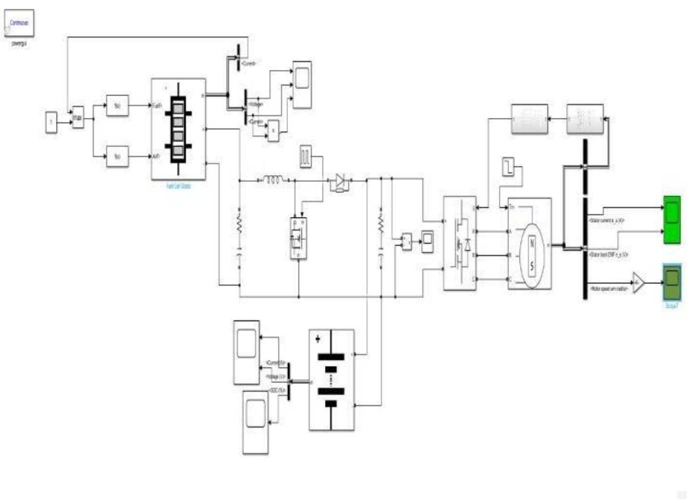

Fig.2: Simulink model of PEM Fuel Cell- Battery Hybrid Electric Vehicle System

1. Simulation result of PEMFC system:

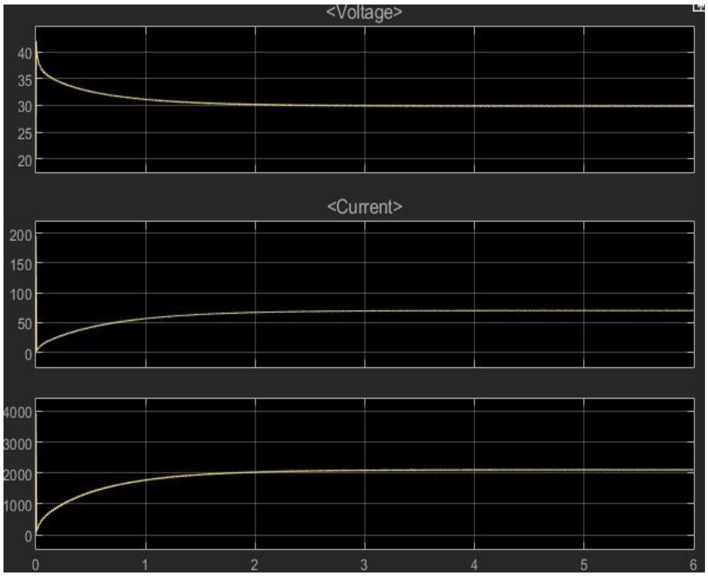

Fig. 3: Simulatio5 result of PEMFC system

2. Simulation result of Battery storage system:

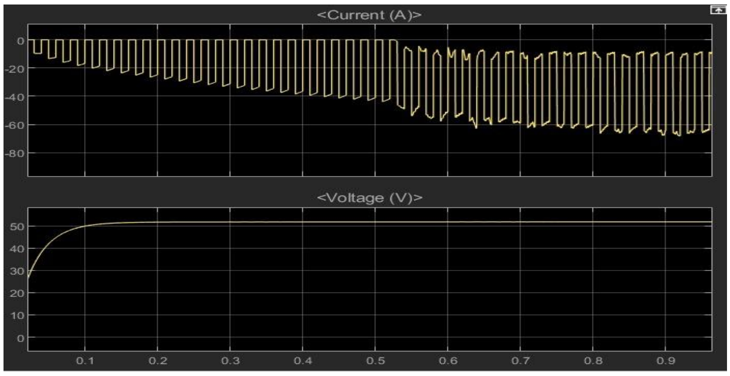

Fig. 4: Simulation result of Battery

3. Simulation result of Battery State Of Charge (SOC):

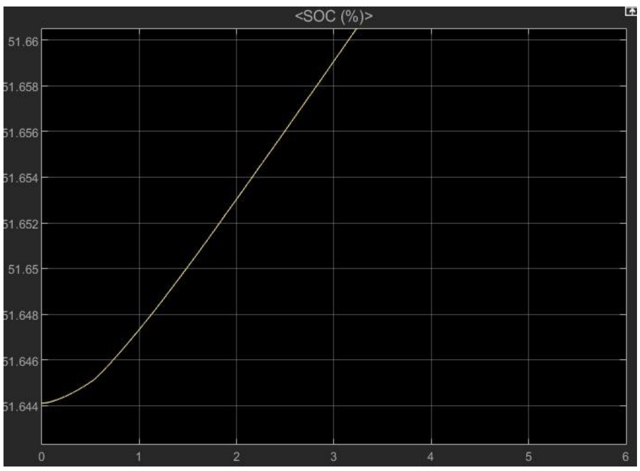

Fig. 5: Simulation result of battery SOC

4. Simulation result of Motor stator winding:

Fig 6: Simulation result of stator winding

5. Simulation result of Motor Speed (RPM):

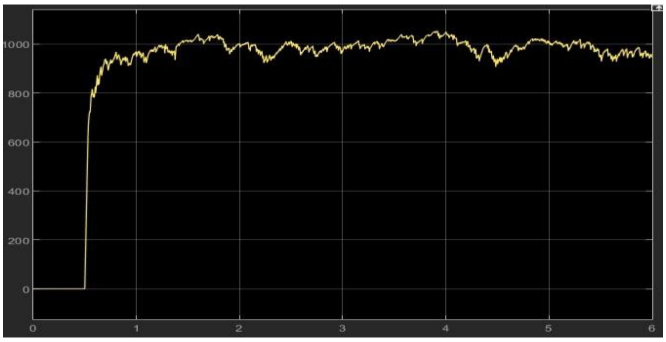

Fig 7: Simulation result of motor speed in rpm

6. RESULTS AND DISCUSSION

The simulation results demonstrate the significant benefits of the proposed Energy Management System (EMS) for Hybrid Electric Vehicles (HEVs) that integrate a Proton Exchange Membrane (PEM) fuel cell and a battery. The optimized power split between the two energy sources led to a notable improvement in fuel efficiency, with the hybrid system achieving up to 20% better fuel economy than traditional internal combustion engine vehicles. This improvement was attributed to the efficient operation of the fuel cell during steady driving conditions and the battery's ability to cover peak power demands without unnecessary fuel consumption.

The EMS also extended the battery lifespan by reducing deep discharges and excessive charging cycles, resulting in a 15% increase in battery life. In terms of environmental impact, the hybrid system contributed to a 30% reduction in CO2 emissions, highlighting the potential of fuel cell-based HEVs to mitigate climate change. These findings suggest that an effective EMS, which dynamically adjusts the power distribution between the fuel cell and battery, can significantly enhance the overall performance, efficiency, and sustainability of HEVs. The results also indicate that this approach can be scalable to different types of hybrid vehicles, offering promising solutions for future green transportation systems.

7. CONCLUSION AND FUTURE SCOPE

In conclusion, hybrid systems combining batteries and PEM fuel cells offer a promising solution for the future of sustainable transportation. The integration of these two technologies allows for optimized energy management, where the fuel cell primarily handles steady-state power demands while the battery supports transient power needs like acceleration. This dual source system enhances overall fuel efficiency, extends vehicle range, and significantly reduces emissions, as the PEM fuel cell generates electricity through a clean electrochemical process, emitting only water vapor, improve battery life by preventing deep discharges and maintaining a steady state of charge, which is crucial for the longevity of the battery. However, the widespread adoption of these hybrid systems faces challenges, particularly the high initial cost of the vehicle due to the expensive components of both the fuel cell and the battery. Despite these challenges, the potential for reduced carbon emissions and the development of hydrogen infrastructure offers a bright future for fuel cell hybrid vehicles. These hybrid systems could play a crucial role in reducing the environmental impact of transportation, offering an effective solution for sustainable mobility, The future scope of Proton Exchange Membrane (PEM) fuel cells- battery HEV is promising, driven by advancements in technology, materials science, and a growing demand for sustainable energy solutions. Here are several key areas of future development:

1. **Advancements in Hydrogen Infrastructure**: As The future of fuel cell hybrid vehicles depends heavily on the expansion of hydrogen refueling stations. As infrastructure grows, it will become easier and more convenient for consumers to adopt hydrogen-powered vehicles, accelerating the shift toward sustainable transportation.

2. **Enhanced Energy Management Strategies:** Future energy management systems could incorporate AI-driven predictive algorithms to optimize power distribution between the battery and fuel cell. This would enhance vehicle efficiency, improve performance under varying conditions, and further reduce energy consumption and emissions.

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