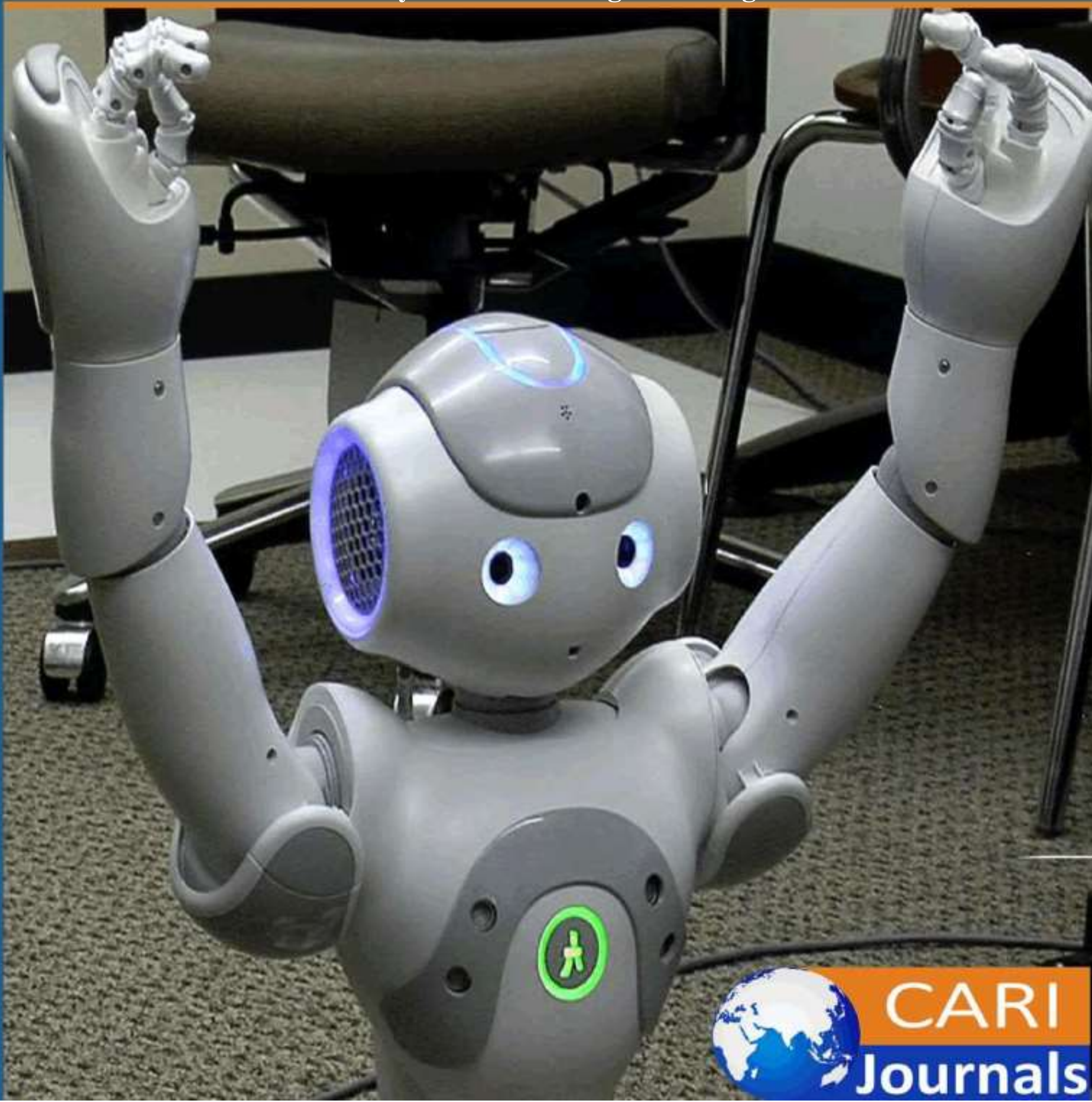
International Journal of
Computing and
Engineering
(IJCE)

Dynamic Power Sharing and DC-Bus Stability in PEM Fuel Cell–Battery Marine Microgrids Using PI Control



CARI Journals

International Journal of Computing and Engineering
ISSN 2958-7425 (online)
Vol. 8, Issue No. 1, pp 45 - 65, 2026
www.carijournals.org

Dynamic Power Sharing and DC-Bus Stability in PEM Fuel Cell–Battery Marine Microgrids Using PI Control

Hussam Adel Banawi
Post Graduate Student, King Abdulaziz University
https://orcid.org/0009-0005-1503-0178

Accepted 5th January, 2026, Received in Revised Form 18th January, 2026, Published: 23rd Jan, 2026

Abstract

Purpose: The purpose of this study is to evaluate the feasibility and performance of a classical proportional–integral (PI)-based energy management strategy for a fuel cell–battery hybrid marine DC microgrid. The work aims to determine whether deterministic and low-complexity control can ensure stable, robust, and certification-ready operation for low-emission marine propulsion systems under realistic mission conditions.

Methodology: A hybrid marine DC microgrid composed of a proton exchange membrane fuel cell and a lithium-ion battery energy storage system is developed and coordinated through a multi-loop PI-based energy management system. The battery operates as a grid-forming unit responsible for DC-bus voltage regulation, while the fuel cell supplies the steady-state propulsion and auxiliary power demand under ramp-rate constraints. System performance is assessed through a one-hour mission-based simulation representative of coastal vessel operation, focusing on DC-bus voltage stability, power sharing behavior, battery state-of-charge evolution, fuel cell tracking performance, hydrogen consumption, and instantaneous power mismatch.

Findings: The simulation results demonstrate stable DC-bus voltage regulation within ±5% of the nominal value throughout the mission. Battery state of charge remains within the predefined operating range of 20%–80%, indicating controlled battery utilization and avoidance of deep cycling. The fuel cell supplies approximately 90% of the total energy demand, while the battery absorbs short-duration load transients and limits fuel cell exposure to rapid power variations. Power mismatch remains bounded and short-lived, confirming effective coordination between system components under dynamic operating conditions.

Unique contribution to theory, practice and policy: This study provides quantitative evidence that a properly structured PI-based energy management strategy can achieve reliable and low-emission operation in a megawatt-scale fuel cell–battery marine DC microgrid without reliance on computationally intensive optimization or artificial intelligence techniques. The findings reinforce the relevance of classical control methods for marine power systems, offering a transparent, robust, and certification-friendly solution for industry practitioners and supporting policymakers in the development of practical decarbonization pathways for the maritime sector.

Keywords: *Marine DC microgrid; Fuel cell–battery hybrid system; PI-based energy management; Hydrogen propulsion; Low-emission vessels*

1. Introduction

The maritime transportation sector is at a vital turning point, based on stringent regulations on environmental concerns and growing operational efficiency requirements and the volatility of fuel costs, limiting the usefulness of conventional diesel-based propulsion systems. The International Maritime Organization (IMO) has been continuously tightening the restrictions for emission of greenhouse gases and local air pollutants, so the organization has created a mandatory requirement for shipowners and ship designers to seek alternative power solutions that are capable of meeting the long-term decarbonization targets while not compromising reliability and safety [1]. Conventional marine diesel engines—despite their maturity and their ability to provide high power density—have serious disadvantages, particularly under variable and partial load conditions. These downsides include lower efficiency, significant CO_2, NOx, and SOx emissions, increased acoustic and vibrational noise, and ever-increasing life-cycle costs from fuel price volatility and regulatory costs [2]. Owing to this, the development of low-emission marine powertrains has become a key research and industrial priority.

Among the alternative technologies being considered, hydrogen-based proton exchange membrane fuel cells (PEMFCs) have attracted more and more attention in marine applications [3]. According to [5], PEMFCs directly transform the chemical energy of hydrogen into electricity by an electrochemical reaction, with water and heat being the by-products and no local emissions being produced while in operation. From the point of view of efficiencies, fuel cells are more efficient than internal combustion engines at partial load, an aspect that is of great interest for loads in vessels for which the propulsion profile varies considerably [6]. Moreover, the low noise and low vibration characteristic of PEMFCs improves the comfort on board, making it appealing for passenger vessels such as ferries and coastal craft [7]. Nevertheless, PEMFCs have intrinsic limitations that prevent their use in marine propulsion on their own and are particularly limited in terms of their tolerance to fast load variations and ramp rate [12]. To overcome these drawbacks, battery energy storage systems (BESSs) are often used with missing fuel cells to form hybrid powertrains [4]. In a fuel cell-battery hybrid architecture, the fuel cell is generally used as the prime energy source, which helps the generation of average or steady-state power requirements while the battery is in standby, which can provide high power density for addressing fast transients, propulsion accelerations, and sudden load disturbances [13]. This role division helps to define dynamic stress on the fuel cell, to increase the overall efficiency of the system, and to lengthen the lifespan of the components [7]. From the system design point of view, the combination of fuel cell and battery offers a favorable combination of energy density and power density, making such hybrid designs suitable for short- and medium-range marine vessels operating under dynamic mission profiles [11].

Recent research efforts have highly focused on the design of advanced energy management systems (EMSs) for coordinating energy sharing among fuel cells, batteries, and other systems on board (SoB) [9]. A wide range of optimization-based and intelligent control strategies have been proposed, such as model predictive control, fuzzy logic control, evolutionary algorithms, and reinforcement learning [20]. These approaches are able to achieve nearly optimum fuel consumption, better utilization of the components, and predictive handling of the prospective load demands [9]. However, their implementation for shipboard applications is difficult. Heavily computation-intensive EMSs often need extensive computational resources, detailed system models, and exhaustive tuning of these, which restricts the applicability of such methods in safety-critical marine systems [16].

On the other hand, proportional-integral (PI)-based control is still the backbone of most industrial power management and automation systems in the marine environment because of its simplicity, transparency, and deterministic behavior [4]. The use of PI controllers is computationally lightweight, and they have been well accepted by classification societies, so this makes them attractive for real application use in the marine world [6]. In spite of these benefits, PI-based energy management strategies are generally considered to be suboptimal compared to advanced optimization methods, and their performance in large-scale fuel cell battery marine DC microgrids has not been sufficiently quantified under realistic operating conditions [8].

This paper addresses this lacuna by investigating a hybrid PEMFC-battery DC microgrid for marine propulsion and the auxiliary loads, coordinated through a multi-loop PI-based energy management system. The proposed architecture follows a DC distribution scheme within which the fuel cell supplies the dominant portion of the propulsion and hotel loads, and the battery is a fast-response buffer accommodating transient fluctuations of power and imposing operational constraints [8]. Unlike the work on the integration of renewable energy resources or complex optimization algorithms, the focus of the present work is deliberately on the essential interaction of the fuel cell, the battery, and the DC bus, with the aim of examining stability, robustness, and practical implementability on the basis of classical control techniques [4].

A mission contribution simulation representative of the operation of a coastal ferry is used to determine system performance under a 1 hr operational profile [7]. Some important performance characteristics include DC-bus voltage regulation, battery state-of-charge evolution, fuel cell ramp-rate compliance, hydrogen consumption, and instantaneous mismatch of power [8]. By analyzing time domain responses under dynamic, demanding conditions, the study provides a focused evaluation of the suggested control strategy.

The main value of this piece of work is to prove that a properly designed PI-based energy management strategy is capable of providing stable and reliable operation for a megawatt-scale fuel cell-battery marine powertrain without a computationally intensive optimization or artificial intelligence-based strategy [4]. The results show that classical control is a feasible and certifiable solution for the next generation of low-emission vessels, provided it is properly structured and tuned.

2. Literature Review

The development of low-emission marine power systems has commanded significant interest from the research community over the last twenty years, driven mainly by the need for such systems to comply with regulations and boost their operational efficiency [1]. The present section overviews previous efforts pertinent to fuel cell-battery hybrid marine powertrains with regard to system architectures, energy management strategies, and control methods. The goal is to place the present study in the context of the existing knowledge and to outline the remaining research gaps.

2.1 Fuel Cell-Based Marine Power Systems

Early studies on fuel cell applications to marine vessels were largely feasibility studies and small-scale demonstrators [14]. Initial work had shown PEMFCs could suitably replace or supplement diesel generators for auxiliary loads and low-power propulsion, so that the fundamental benefits of fuel cells in terms of zero local emissions, low noise, and improved efficiency at partial load were proven [5]. Nonetheless, these studies revealed fundamental difficulties as well, for example, low power density, low hydrogen density, and issues in the ability to respond to sudden load fluctuations [12].

With the development of fuel cell technology to a stage of maturity, further research investigated larger-scale marine applications, including passenger ferries as well as short-range commercial ships [7]. These investigations determined the technical viability of megawatt-class fuel cell systems as properly integrated in shipboard electrical architectures [3]. However, most authors concluded that fuel cells should not be used as stand-alone power sources because of their limited dynamic response and degradation potential under frequent load cycling [12]. This insight sparked the widespread use of hybrid architectures that combine fuel cells and electrical energy storage [4].

2.2 Fuel Cell-Battery Hybrid Architectures

Fuel-cell-battery hybrid systems are now the dominant system in the literature for marine applications [6]. In such architectures the fuel cell is usually sized according to the average level of propulsion demand, and the battery is dimensioned according to the transient loads, peak shaving, and fast power fluctuations [13]. Multiple studies have shown that hybridization brings considerably higher overall system performance by leveling the operation of the fuel cell and lowering hydrogen consumption in dynamic maneuvers [19].

Various hybrid topologies have been suggested, such as AC-coupled and DC-coupled topologies [4]. DC microgrids, in particular, have gained more and more interest because of improved efficiency, a lower number of conversion stages, and higher controllability when they include several sources of power [21]. Research has shown that DC-based shipboard power systems are suitable for fuel cell/battery integration because they allow flexible power sharing and simplified voltage regulation [8]. Nevertheless, DC microgrids also pose stability issues, particularly where constant power loads and strict control on converters are involved, and thus require effective control methods [16].

2.3 Energy Management Strategies for Hybrid Marine Systems

A large part of literature focuses on the design of energy management systems (EMSs) for coordinating power flow from fuel cells, batteries, and ship loads [9]. Existing EMS approaches are generally divided into rule-based methods and optimization-based approaches [20]. Rule-based EMSs depend on predefined logic or feedback control laws for power allocation based on system states such as load demand and battery state of charge. These methods are attractive because of their ease, low computational requirements, and ease of implementation [4]. Classical proportional-integral control is often used to control the DC-bus voltage and the current from the battery with the fuel cell [6]. Several studies have shown that PI-based strategies are able to preserve the voltage stability and acceptable power sharing in hybrid marine microgrids [8]. However, rule-based approaches are often criticized for not being optimal in the sense of fuel consumption and component degradation [20].

Optimization-based EMSs aim at improving the performance by solving constrained optimization problems either online or offline [9]. Techniques like dynamic programming, model predictive control, genetic algorithms, and reinforcement learning have been widely reported [20]. Such methodologies aim at realizing better fuel efficiency and early load handling by anticipating the future [9]. Nonetheless, optimization-based EMSs are also hampered by practical constraints in marine applications, such as high computational demands, reliance on accurate models of the system, and low transparency, which pose challenges in applying them to real-life applications and certification [16].

2.4 Studies and PI-Based Approaches with Control Orientation

Although more sophisticated EMS techniques are present in the current publications, PI-based control is the most widely used control strategy for industrial marine systems [4]. Numerous research reports have shown that the PI controllers can achieve stable DC-bus voltage regulation and power sharing between fuel cells and batteries properly tuned can be achieved under variable load circumstances [6]. Comparative analyses often show the performance gap between PI-based control and the more advanced optimization techniques is marginal, especially when, for example, system objectives may not be optimality but rather may focus on robustness and safety [8].

Nevertheless, most of the PI-based studies in the literature are of limited scope. Many concentrate on laboratory-scale, low-power systems or stationary microgrids as opposed to full-scale marine propulsion [13]. Others assess the performance of controllers under simplified or steady-state profiles of load that are not representative of actual vessel operation [20]. As a result, there is insufficient evidence to determine whether classical PI control can be used to reliably manage megawatt-scale fuel-cell-battery marine powertrains under realistic mission conditions [8].

2.5 Research Gap and Motivation

Based on the literature review, there can be identified a few gaps. First, although fuel-cell/battery hybrid architectures have been firmly established, their dynamic behavior under mission-based marine load profiles is yet to be investigated in some detail [21]. Second, most of the recent research focuses on optimization-heavy EMS approaches, which are of limited applicability for certified shipboard environments [16]. Third, the capabilities of PI-based energy management strategies at the system level have not been systematically quantified for large-scale marine DC microgrids, in particular in terms of voltage stability, ramp-rate compliance, and robustness [8].

The present study addresses these gaps by focusing only on the fuel cell-battery hybrid marine power system controlled through a multi-loop-based PI-based EMS. By considering the evaluation of system performance based on a realistic mission profile and focusing on stability and robustness as opposed to theoretical optimality, this work is aimed at giving practical insight into the viability of classical control strategies for next-generation low-emission marine vessels [4].

3. System Description and Mathematical Modeling

This section outlines the setup of the proposed fuel cell-battery marine power system and introduces the mathematical models used to describe the main components of the system. The modelling strategy is control-orientated and mission-level with the intention of capturing relevant electrical and energetic dynamics that prevail with regards to energy management and stability assessment.

3.1 Overall System Architecture

The proposed system is a hybrid marine DC microgrid consisting of the following components: proton exchange membrane fuel cell (PEMFC), lithium-ion battery energy storage system (BESS), propulsion and auxiliary loads and associated power electronics converters. A DC distribution architecture is used to reduce the number of stages in the conversion process and to increase the controllability. All the sources and loads are connected to a common DC-bus at a nominal voltage (500 V). Within this architecture, the fuel cell is the primary source of power that is used to provide the steady-state propulsion power requirements as well as continuous auxiliary loads. The battery acts as a high response buffer to deal with transient variations in load and also to overcome the limitations in the ramp rate of fuel cells. This separation between functions is a reflection of pragmatic hybrid powertrain design principles and helps to reinforce the robustness of the overall system.

3.2 Load Modeling

The sum of electrical demands of the vessel are then separated into propulsion and hotel loads. The propulsion load is modeled as a time-varying power load which summarizes the cruising operation, maneuvering maneuvers as well as fluctuations caused by the sea state.

$$P_{\text{prop}}(t) = P_{\text{avg}} + \Delta P_{\text{sin}}(t) + \Delta P_{\text{rand}}(t)$$

where $P_{\text{avg}}$is the nominal propulsion power, ΔP_{sin}represents low-frequency oscillations associated with speed variations, and ΔP_{rand}captures stochastic disturbances.

The hotel load is modeled as a DC demand with moderate periodic variation:

$$P_{\text{hotel}}(t) = P_{\text{hotel,avg}} + \Delta P_{\text{hotel}}(t)$$

The total vessel electrical load is therefore given by:

$$P_{\text{load}}(t) = P_{\text{prop}}(t) + P_{\text{hotel}}(t)$$

3.3 Fuel Cell Model

The proton exchange membrane fuel cell (PEM) is studied at the power level, putting focus on the electrical output characteristics and dynamic limitations of the PEM fuel cell. The electrical output power of the fuel cell is limited by the rated capacity of the cell:

$$0 \le P_{\text{FC}}(t) \le P_{\text{FC,max}}$$

In order to account for the physical limitations that exist in the way reactants are regulated in flow and temperature, a ramp rate limitation is implemented:

$$\left| \frac{dP_{\text{FC}}(t)}{dt} \right| \le R_{\text{FC}}$$

where $R_{\text{FC}}$is the maximum allowable power ramp rate.

Hydrogen consumption is calculated on the basis of the cumulative electrical energy supplied by the fuel cell, using a model that is assumed to have constant efficiency:

$$m_{\text{H}_2}(t) = \frac{1}{\eta_{\text{FC}} \cdot \text{LHV}_{\text{H}_2}} \int_0^t P_{\text{FC}}(\tau)\, d\tau$$

where $\eta_{\text{FC}}$is the fuel cell efficiency on a lower heating value basis and $\text{LHV}_{\text{H}_2}$is the hydrogen lower heating value.

3.4 Battery Energy Storage Model

The battery energy storage system is modeled using an energy-centric formulation. The state of charge (SOC) is defined as: the quotient of the residual stored energy and the nominal battery capacity:

$$\text{SOC}(t) = \frac{E_{\text{batt}}(t)}{E_{\text{batt,max}}}$$

The SOC dynamics are governed by the battery power exchange:

$$\frac{d\,\mathrm{SOC}(t)}{dt} = -\frac{P_{\mathrm{batt}}(t)}{E_{\mathrm{batt,max}}}$$

where positive P_{batt}denotes battery discharge. Operational constraints are imposed as:

$$\mathrm{SOC}_{\mathrm{min}} \leq \mathrm{SOC}(t) \leq \mathrm{SOC}_{\mathrm{max}}$$
$$|\, P_{\mathrm{batt}}(t) \,| \leq P_{\mathrm{batt,max}}$$

These limits address excessive battery degradation and are associated with realistic limitations in terms of the convertor performance and thermal behaviour.

3.5 DC Bus Dynamics

In this investigation the DC bus is modeled as a lumped capacitance to represent the global dynamics of the DC link of the system. Differences in power injections of DC - side sources and demands of the loads determine the temporal evolution of the DC - bus voltage:

$$C_{\mathrm{dc}}\,\frac{dV_{\mathrm{dc}}(t)}{dt} = \frac{P_{\mathrm{dc,src}}(t) - P_{\mathrm{dc,load}}(t)}{V_{\mathrm{dc}}(t)}$$

where $C_{\mathrm{dc}}$is the equivalent DC-link capacitance, $P_{\mathrm{dc,src}}$is the total DC-side power injected by the fuel cell and battery, and $P_{\mathrm{dc,load}}$is the hotel load.

The DC-bus voltage is allowed to vary within acceptable bounds:

$$V_{\mathrm{dc,min}} \leq V_{\mathrm{dc}}(t) \leq V_{\mathrm{dc,max}}$$

With $V_{\mathrm{dc,min}} = 0.95V_{\mathrm{dc,nom}}$ and $V_{\mathrm{dc,max}} = 1.05V_{\mathrm{dc,nom}}$.

3.6 Power Balance Constraint

At every instant, the overall system must satisfy the power balance condition:

$$P_{\mathrm{FC}}(t) + P_{\mathrm{batt}}(t) = P_{\mathrm{prop}}(t) + P_{\mathrm{hotel}}(t) + P_{\mathrm{loss}}(t)$$

where $P_{\mathrm{loss}}(t)$represents aggregated conversion losses, which are neglected in this study for simplicity.

3.7 Modeling Assumptions and Scope

In order to ensure analytical clarity and a focused analysis of energy-management behavior, the following assumptions have been used in the present analysis efforts: (i) power-electronic converters are ideal, (ii) elaborate electromagnetic dynamics at the machine level are aggregated to the level of load profiles, and (iii) thermal and ageing phenomena are not represented. Although these sorts of idealizations make representation simpler, the resulting model is nonetheless faithful in representing the principal interactions between the fuel cell, the battery and the DC bus in the dynamic marine operation.

The mathematical model presented in this part follows the theoretical foundation of the control scheme that can be elaborated in the next part because, here, a multi-loop proportional-integral (PI)-structured energy management system is designed to coordinate power output between the star and ensure that the system behaves in a manner that provides stability in operation.

4. Control Strategy: Pi-Based Energy Management System

In this section, the proposed control architecture, and the respective control laws, which enable the distribution of power between the fuel cell and the battery, and maintain the stability of the DC bus are outlined. To ensure that there is no deterministic behavior, reduce the response load and fulfil the stringent requirement of certified marine systems, the strategy uses classical proportional integral (PI) controllers.

4.1 Control Architecture Overview

The hierarchical but completely deterministic overall control structure is adopted. Inner control loops in the locality control currents in converters and impose physical limits, and the higher-level energy-management layer coordinates the fuel cell and battery depending on the system conditions. The DC bus is used as the common coupling node, the deviation of which is used as a real-time signal of power imbalance.

The important control objectives are:

1. Keep DC-bus voltage at an acceptable level of (±5) of the nominal value (500 V).
2. Respect fuel cell power and ramp-rate constraints.
3. Keep the battery state of charge (SOC) within the predefined operating window.
4. Make sure that there is instant power balance in both dynamic propulsions and hotel loads.

4.2 DC-Bus Voltage Regulation

The DC bus voltage is the most critical relation of power balance of the system. Any discrepancy between generation and load causes a voltage difference that will be rectified by a coordinated source control.

The DC-bus voltage error is defined as:

$$e_V(t) = V_{\mathrm{dc,ref}} - V_{\mathrm{dc}}(t)$$

A PI controller generates a corrective power command associated with DC-side support:

$$P_V(t) = K_{p,V}\, e_V(t) + K_{i,V} \int e_V(t)\, dt$$

In the given architecture, the fuel cell provides the steady-state DC load, which can be attributed to the hotel loads, and that the battery plays its role in only a few cases when the voltage changes significantly due to the loads changes or the limitations of the fuel cell ramp rates. This arrangement helps to eliminate aggressive battery cycling and, by extension, improves battery life.

4.3 Fuel Cell Power Control

The fuel cell operates as the primary energy source and is commanded to supply the average propulsion and hotel load. Its reference power is computed as:

$$P_{\mathrm{FC,ref}}(t) = P_{\mathrm{prop}}(t) + P_{\mathrm{hotel}}(t) - P_{\mathrm{batt}}(t)$$

To reflect physical constraints, the fuel cell power is limited by both rated capacity and ramp rate:

$$0 \le P_{\mathrm{FC}}(t) \le P_{\mathrm{FC,max}}$$

$$\left| \frac{dP_{\mathrm{FC}}(t)}{dt} \right| \le R_{\mathrm{FC}}$$

The actual fuel cell output follows the reference through a rate limiter:

$$P_{\mathrm{FC}}(t) = \mathrm{sat}\left(P_{\mathrm{FC}}(t-\Delta t) + \mathrm{sat}\left(P_{\mathrm{FC,ref}}(t) - P_{\mathrm{FC}}(t-\Delta t), \pm R_{\mathrm{FC}}\Delta t\right), [0, P_{\mathrm{FC,max}}]\right)$$

This formulation ensures smooth fuel cell operation and prevents rapid power fluctuations that could accelerate degradation.

4.4 Battery Power Control and SOC Management

The battery handles the rapid local power transients that are impossible to address with the fuel cell due to limitation of the ramp-rate. The calculated battery supplied power is calculated as the instant error:

$$P_{\mathrm{batt}}(t) = P_{\mathrm{load}}(t) - P_{\mathrm{FC}}(t)$$

To prevent excessive cycling, battery operation is constrained by both power and SOC limits:

$$| P_{\mathrm{batt}}(t) | \le P_{\mathrm{batt,max}}$$

$$\mathrm{SOC}_{\min} \le \mathrm{SOC}(t) \le \mathrm{SOC}_{\max}$$

A deadband is applied around zero power mismatch to avoid control chattering:

$$P_{\mathrm{batt}}(t) = \begin{cases} 0, & | P_{\mathrm{load}} - P_{\mathrm{FC}} | < \Delta P_{\mathrm{db}} \\ \mathrm{sat}(P_{\mathrm{load}} - P_{\mathrm{FC}}), & \text{otherwise} \end{cases}$$

The SOC dynamics follow:

$$\frac{d\,\mathrm{SOC}(t)}{dt} = -\frac{P_{\mathrm{batt}}(t)}{E_{\mathrm{batt,max}}}$$

This formulation ensures that the battery acts primarily as a transient buffer rather than an energy-shifting device.

4.5 Power Balance Enforcement

At each control step, overall power balance is enforced implicitly through DC-bus dynamics:

$$P_{\mathrm{FC}}(t) + P_{\mathrm{batt}}(t) = P_{\mathrm{prop}}(t) + P_{\mathrm{hotel}}(t)$$

Any provisional imbalance finds its expression in a disparity in the DC-bus voltage, which is thus removed in PI-based control loops. This indirect enforcement eliminates the necessity of its explicit optimization or prediction whereas maintaining the stability of operations.

4.6 Stability and Robustness Considerations

The proposed PI-based EMS has the following stability characteristics:

- Voltage stability: DC-bus voltage remains bounded within ±5% under all simulated operating conditions.
- Fuel cell protection: Ramp-rate and power limits prevent aggressive operating points.
- Battery protection: SOC constraints and deadband logic minimize unnecessary cycling.
- Deterministic behavior**:** Control actions are fully transparent and repeatable.

The current strategy is not based on predicting future loads using optimisation or AI, which is unlike other EMSs that operate on the premise of future predictions and training. Every control measure is based on measurements at any moment, thus making the approach to be applicable to real-time implementation under shipboard and certification.

5. Results and Discussion

The current section presents the simulation results of the proposed fuel-cell-battery marine DC microgrid based on a one-hour mission profile typical of and representative of coastal ferry operation. The purpose of analysis is to evaluate the dynamic performance, stability and robustness for the performance of PI based energy management system when exposed to realistic propulsion and auxiliary load variations.

Contrary to the emphasis on isolated signals the following results are presented in a way to highlight the interaction between power generation, load demand, DC-bus regulation and component level constraints. Key performance indicators are power-sharing behavior at any one time between the fuel cell and battery, power mismatch between the fuel cell and battery at any one time, voltage stability at the DC-bus, battery state-of-charge evolution, tracking performance of the fuel cell and hydrogen consumption characteristics.

The results are discussed in relation to individual figures, each of which describes a specific aspect of system behavior. Emphasis is given to demonstrating stable operation, bounded deviations and coordinated, source interaction without dependence on optimization-based/predictive control strategies. This approach gives a short evaluation on the suitability of classical PI-based energy management for megawatt scale low-emission marine power systems.

Figure 1 shows the power generation stack of the hybrid fuel cell - battery system vs the total electrical load for the one hour mission. The stacked-area representation shows the individual contributions of fuel cell and the battery, the line laid on top shows the total load demand. The results show that the fuel cell is the primary source of electrical power during the entire mission as it operates at or close to nominal power. This validates its function as the main source of energy to take care of the steady state propulsion loads and hotel loads. The battery has an intermittent contribution and is limited in the duration of discharge available, coinciding with the periods of rapid increase in load. These events occur when the fuel cell production is temporarily limited by the fuel cell ramp-rate limitation and is unable to follow abrupt changes of power demands instantaneously.

The good correlation between the total generation stack and the load profile illustrates good real-time power coordination. No sustained power deficit is observed indicating successful operation of the proposed PI based energy management system to maintain supply adequacy under dynamic operation. Moreover, the small magnitude and duration of battery discharge emphasize the idea that battery is used strictly as a transient buffer, rather than as a primary energy source, so that it minimizes unnecessary battery cycling and contributes to the long-term system durability. These observations are consistent with prior studies on PEMFC–battery hybrid architectures, which similarly report that the fuel cell supplies steady propulsion loads while the battery buffers rapid transients due to ramp-rate constraints [7], [13]. This agreement supports the established design principle of transient hybridization in marine systems. However, optimization-based and predictive EMS approaches reported in the literature have shown modest gains in long-horizon fuel minimization and ageing management [9], [20], suggesting a trade-off between operational optimality and the deterministic, certification-oriented deployment offered by classical PI control.

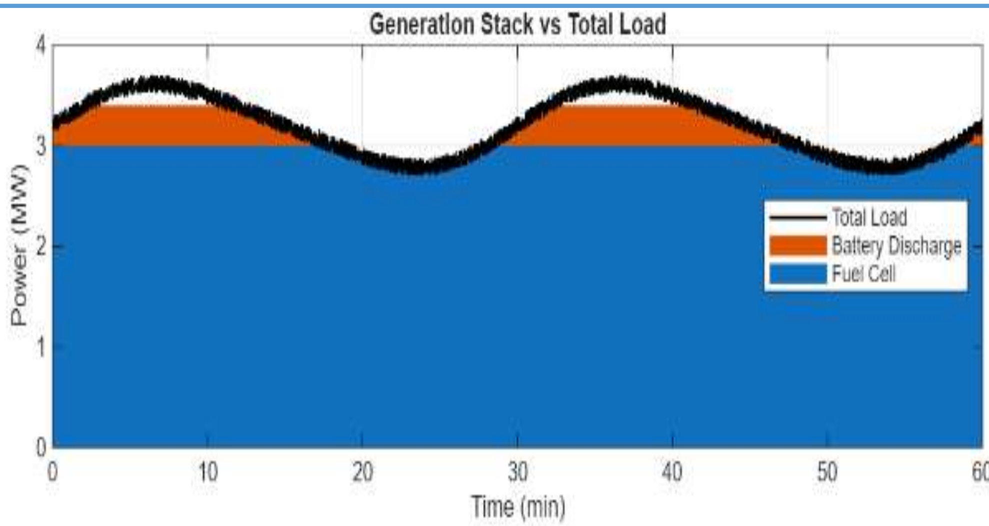


Figure 1. Generation Stack versus Total Electrical Load

For a mission of 1 hour, Figure 2 depicts the power mismatch in the system during a mission, that is, the total electrical load minus the total electrical power generated in the system at a particular time. Positive values represent temporary deficits in generation, and negative values are the times when there is excess generation.

As you can see, the mismatch is still centered around zero for most of the mission, and this is evidence of good on-the-fly power balancing by the proposed energy management system based on a PI. Noticeable deviations happen especially during times of rapid load variation, in which the fuel cell is temporarily short by its ramp rate constriction and cannot instantly trace the power demand. In these intervals, the battery will perform transient support and minimize the magnitude and duration mismatches.

Quantitatively, the root mean square (RMS) mismatch reported of about 89.3 kW and maximum deviation of 283.5 kW are at small scales as compared to the megawatt-scale system power. These values prove that power imbalance is maintained in good control even in aggressive operating conditions. Importantly, mismatch peaks are of a limited duration and decay quickly, without the need to apply predictive or optimization-based control mechanisms, confirming the robustness of the control strategy. These mismatch characteristics are consistent with previous hybrid fuel cell–battery studies, which also report bounded transient imbalance arising from fuel-cell ramp-rate limitations and short-duration battery compensation [7], [13], [20]. This agreement supports the view that deterministic PI-based coordination can achieve acceptable real-time power balancing in marine microgrids without predictive scheduling. However, optimization-based and predictive EMS approaches reported in the literature have demonstrated marginal improvements in long-horizon fuel minimization and component ageing control [9], [20], suggesting a trade-off between operational optimality and deterministic, certification-ready implementation.

International Journal of Computing and Engineering
ISSN 2958-7425 (online)
Vol. 8, Issue No. 1, pp 45 - 65, 2026

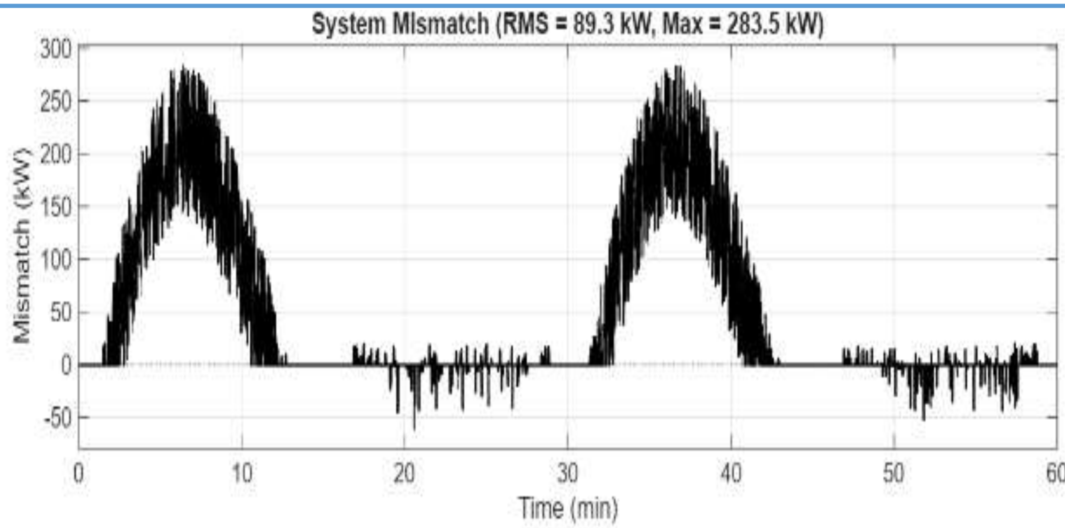


Figure 2. System Power Mismatch under Dynamic Operation

Figure 3 shows the deviation of the DC - bus voltage from the normal nominal DC voltage over the full one - hour duration of the mission as a percentage value. The shaded bounds are the tolerable operating limits of ±5%, which are usually used in the marine DC power system to ensure safe and reliable operation of power electronic converters and on-board loads.

The results show that the voltage of the DC-bus voltage remains tightly regulated to its nominal value during the entire mission with deviations effectively being limited within prescribed limits. The small deviation in the voltage measured close to zero voltage during the operating period suggests that involuntary power imbalances are compensated very quickly by the concerted action of fuel cell and battery in cooperation with the natural buffering effect of the DC link capacitance.

The lack of oscillatory behavior and persistent voltage excursions shows the dynamic stability of the proposed DC microgrid under very variable load conditions. This result confirms that the PI based energy management system is adequate to ensure voltage stability without the utilization of advanced voltage optimization techniques and predictive control techniques, supporting its suitability for real time marine applications. These voltage stability results are consistent with previous hybrid marine DC microgrid studies, which also report that PI-based regulation can maintain DC-bus voltage within acceptable limits under variable load conditions [6], [8]. Such agreement reinforces the suitability of classical feedback control for certification-oriented shipboard environments. However, predictive and optimization-based EMS approaches have been shown to offer marginal improvements in long-horizon efficiency and degradation metrics [9], [20], indicating a trade-off between operational optimality and deterministic, low-complexity implementation.

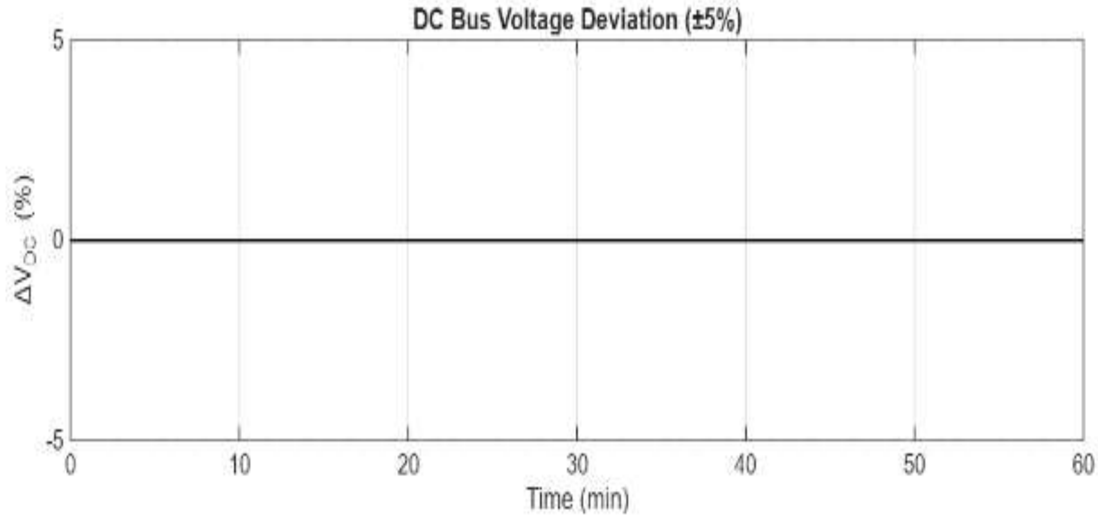


Figure 3. DC Bus Voltage Deviation during Mission Operation

Figure 4 shows the evolution of the battery state of charge (SOC) during the one-hour mission. The battery is initialized at 50% SOC and steadily reduces to about 40% at the end of the operation. The SOC trajectory does not go out of the predefined operation window, indicating that deep discharge and aggressive cycling are not applied to the battery.

The smooth and monotonic reduction in SOC represents the control strategy in this study, i.e., the battery support is used more for short power transients than for sustained power. The lack of sharp drops in SOC is a confirmation that there are both transient load changes and fuel cell ramp rate limitations that limit the battery discharge events.

From an operational viewpoint, the small SOC excursion shows efficient use of the battery that combines dynamic capability and long-term durability aspects. Maintaining a significant SOC margin at the end of the mission will provide assurance that the battery will be available for later operational cycles or emergency power support, providing reinforcement for the practical suitability of the proposed energy management strategy. These SOC dynamics are consistent with hybrid PEMFC–battery studies, which similarly report that storage operates as a transient buffer with conservative cycling to protect lifetime and avoid deep discharge [4], [7], [13]. This agreement reinforces the view that classical PI-based coordination can achieve durability-aware storage utilization without explicit predictive scheduling. However, optimization-based EMS and ageing-oriented control strategies have demonstrated incremental improvements in long-horizon fuel use and battery degradation management [9], [20], indicating a trade-off between lifetime optimality and deterministic, certification-ready implementation.

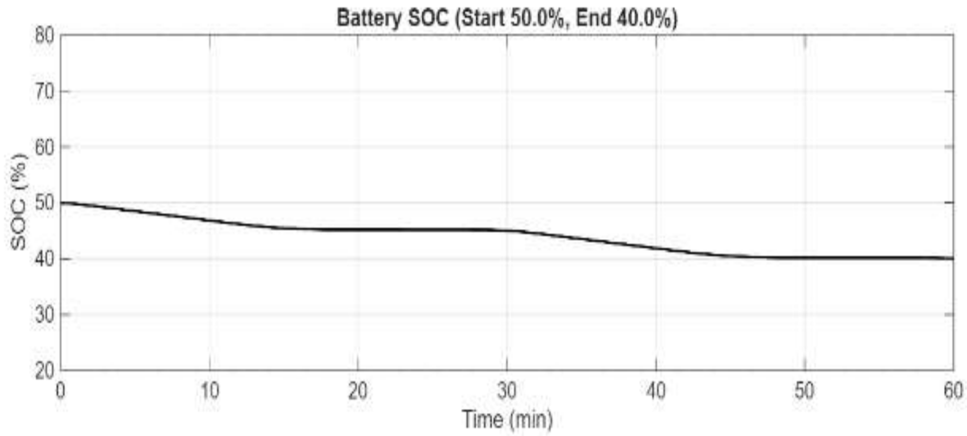


Figure 4. Battery State-of-Charge Evolution over the Mission

The fuel cell power tracking error is the difference between the reference power command issued by the energy management system and the actual fuel cell power output, as shown in Figure 5. Tracking error is close to zero during constant operating periods and is increased during times of rapid load variation.

The reason for these deviations is that the fuel cell, when limited by its ramp rate of response, is unable to track sudden changes in power demand and is limited by its ramp rate limit. During such occasions the battery compensates for the short-term power deficit, which results and the fuel cell is permitted to operate with safe dynamic limits. The maximum absolute tracking error of about 63.9 kW is quite small compared to the fuel cell rated power, which means controlled and smooth operation.

Importantly, the error in tracking is lower and short-lived with no indication of sustained deviation and instability. This behavior validates the effectiveness of the proposed PI based control strategy in protecting the fuel cell from the influence of aggressive power fluctuations without compromising the performance of the entire system. The results can be seen to emphasize the role of the battery as a dynamic buffer separating fast load transients from the fuel cell, mitigating the risks of degradation and increasing the system reliability. These fuel-cell tracking dynamics are consistent with previous studies on hybrid PEMFC–battery control, which also report short-lived ramp-rate–induced tracking errors that are mitigated through battery buffering [7], [13]. Such agreement reinforces the established rationale for hybridization in maritime applications, where transient load fluctuations must be decoupled from the fuel cell to limit degradation and maintain stable operation. However, predictive and optimization-based EMS strategies have demonstrated modest improvements in long-horizon hydrogen minimization and ageing control [9], [20], indicating a trade-off between operational optimality and the deterministic, certification-ready behavior offered by classical PI control.

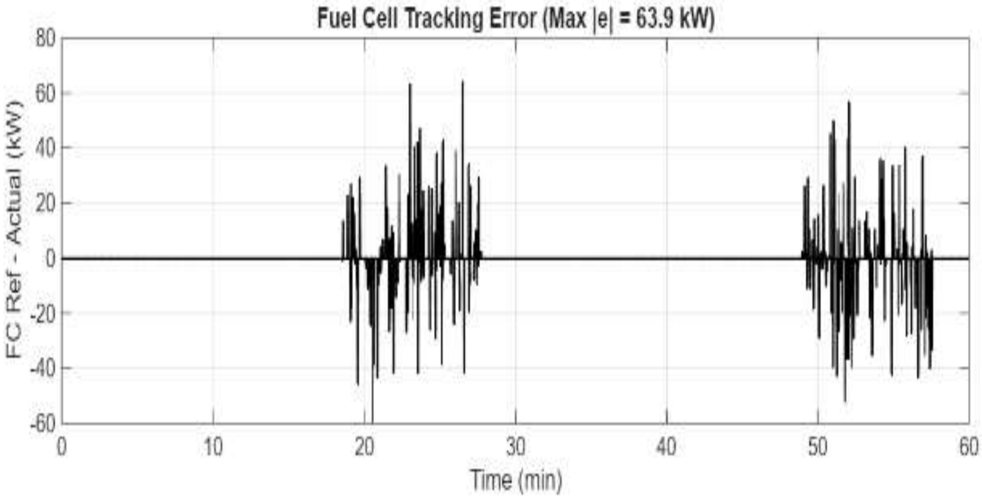


Figure 5. Fuel Cell Power Tracking Error under Ramp-Rate Constraints

Figure 6 shows the cumulative use of hydrogen along with the instantaneous association rate of hydrogen over the one-hour mission. The cumulative consumption of hydrogen varies almost linearly with time and has a total value of about 161.2 kg at the end of the operation. This linear trend is a reflection of the relatively steady average power output of the fuel cell in spite of the presence of dynamic load variations.

The rate of consumption of hydrogen has moderate variations around the nominal rate. Temporary drops in the rate of consumption are related to time periods when the fuel cell output is lowered due to ramp rate limitations or because of transient support provided by the battery. On the contrary, higher rates of consumption are measured when the fuel cell provides a higher proportion of the propulsion demand. This behavior can be understood as successful decoupling of fast load dynamics from the fuel cell, in the sense that short-term transients are mostly taken up in the battery and do not have a direct effect on the hydrogen consumption.

Overall, the hydrogen consumption profile represents smooth and efficient operation by the fuel cells and for the duration of the mission. The lack of sharp peaks in hydrogen consumption indicates that the introduced PI-based energy management strategy is able to limit the abrupt changes of the power of the fuel cell, which is necessary to maintain the efficiency and minimize long-term degradation. These results enhance the verification potential of the hybrid fuel-cell-battery architecture to supply stable power and achieve predictable and manageable hydrogen consumption under realistic marine operating conditions. These hydrogen consumption characteristics are consistent with prior studies on PEMFC-based marine propulsion, which also report that transient load fluctuations have limited influence on hydrogen usage when buffered by battery storage [7], [11]. Such agreement reinforces the view that hybridization effectively decouples fast load dynamics from the fuel cell, allowing near-linear cumulative hydrogen profiles under realistic mission conditions. However, optimization-based and predictive EMS approaches have demonstrated modest improvements in long-horizon fuel minimization and degradation-aware scheduling [9], [20], suggesting a trade-off between fuel-optimal operation and the deterministic, certification-ready implementation afforded by classical PI control.

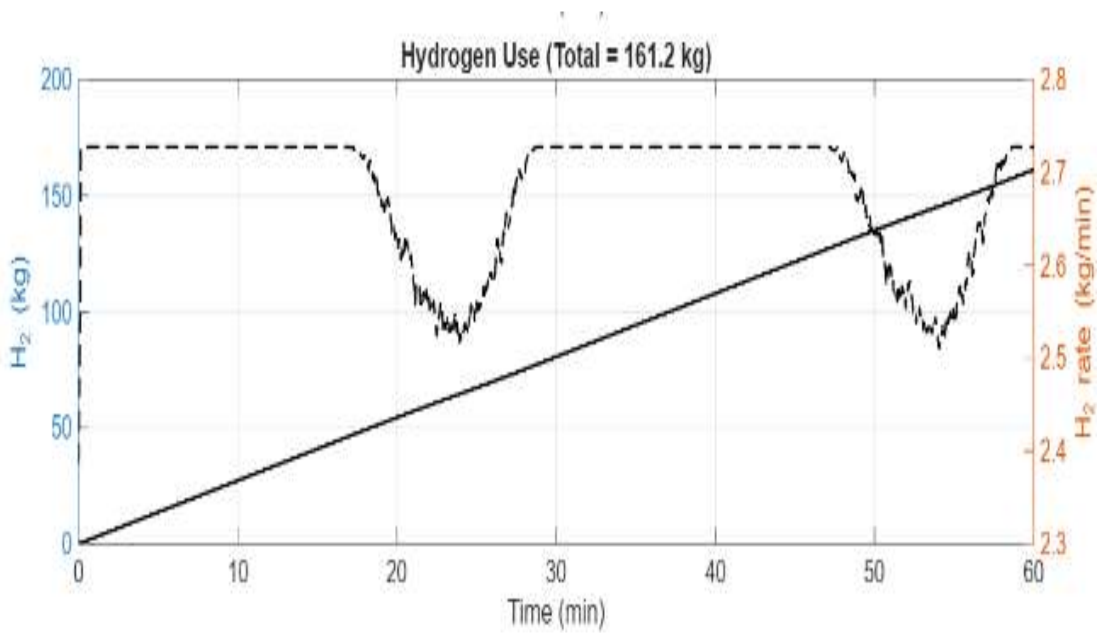


Figure 6. Hydrogen Consumption and Usage Rate during the Mission

Collectively, the results shown in Figures 1-6 give a thorough evaluation of the dynamic performance and robustness of the proposed fuel-cell-battery marine DC microgrid under a realistic mission profile. The other recognized feature of coordinated behavior among all the figures reflects the fact that the PI-based energy management system is successfully integrated to deliver steady-state power, transient support and voltage regulation in a unified and deterministic control system.

Figure 1 confirms good power sharing, with the fuel cell providing the dominant proportion of the electrical demand; with the battery only contributing on short duration transients. This behavior can be seen directly reflected in Figure 2, in which system power mismatch is bounded and centered around zero thus showing the fast compensation of load disturbance without prolonged imbalance. The fact that such low mismatch levels can be maintained is further supported by the results in Figure3 regarding voltage stability which show that the voltage deviations on the DC-bus stay well within the ±5 % limits throughout the mission.

The internal state reactions of the system elements add to this joint operation. As can be seen in Figure 4, the battery state of charge changes smoothly as long as the battery operates within the determined operating window, which truly confirms that the battery is being used in a conservative manner and primarily as a transient buffer. Simultaneously, Figure 5 shows that fuel cell power tracking errors are limited and short lived even in the presence of aggressive load variations, showing the ability of effective fuel cell protection against rapid power fluctuations imposed by ramp rate limitations.

Finally, the hydrogen consumption characteristics in Figure 6 give an energy level view on the system performance. The near linear trend of cumulative hydrogen consumption and the medium degree of variation of instantaneous consumption rate reflect the stable and efficient operation of the fuel cell, which is largely disconnected from the fast load dynamics by the battery. This consistency in the use of hydrogen highlights the efficiency of the proposed control strategy in terms of balancing performance, efficiency and component durability.

Overall, the results presented in Figures 1-6 show that the proposed PI-based energy management strategy is able to provide voltage regulation, power sharing, component dynamics, and hydrogen consumption under realistic marine operating conditions. These results confirm that classical control techniques appropriately structured and tuned should be able to meet the required essential functioning of megawatt size low-emission marine power systems without the necessity of computationally intensive optimization or artificial intelligence methods.

6. Conclusions

The study investigates a fuel-cell–battery hybrid marine DC microgrid controlled by a classical PI-based energy management scheme and evaluated over a realistic one-hour ferry profile. The architecture emphasizes deterministic behavior, transparency, and robustness while deliberately avoiding optimization-based or data-driven control. Results indicate that the fuel cell supplies the steady propulsion and hotel loads, whereas the battery compensates short-duration transients arising from rapid load changes and fuel-cell ramp-rate limits, keeping power mismatch brief and relatively small for a megawatt-scale system. DC-bus voltage remained within ±5% of nominal throughout the mission, and the battery exhibited conservative state-of-charge dynamics without deep cycling. Fuel-cell tracking errors were transient and bounded, and hydrogen consumption followed an almost linear trajectory, signaling stable and efficient operation. These findings suggest that a well-tuned PI strategy can provide reliable power sharing, voltage stability, and component protection in low-emission marine systems. The work supports the continued relevance of classical control methods for practical marine applications where predictability, certification readiness, and implementation simplicity are essential.

Recommendations

Based on the mission-level results, classical PI-based energy management appears sufficiently robust for megawatt-scale fuel-cell–battery marine microgrids under realistic operating profiles. Future work should include hardware validation, degradation-aware modeling, and comparative benchmarks against predictive or optimization-based EMS approaches to clarify performance trade-offs. Extending the analysis to voyage-level operations and multi-stack architectures would also support broader applicability across vessel classes.

REFERENCES

1. IMO, *IMO adopts initial strategy to reduce GHG emissions from ships*, International Maritime Organization, 2018.
2. IMO, *Fourth IMO GHG Study 2020*, International Maritime Organization, 2020.
3. H. Xing, C. Stuart, S. Spence, and H. Chen, "Fuel cell power systems for maritime applications: Progress and perspectives," *Sustainability*, vol. 13, 1213, 2021. https://doi.org/10.3390/su13031213
4. R. D. Geertsma et al., "Design and control of hybrid power and propulsion systems for smart ships: A review," *Applied Energy*, vol. 194, pp. 30–54, 2017. https://doi.org/10.1016/j.apenergy.2017.02.060
5. J. M. Andújar and F. Segura, "Fuel cells: History and updating," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 2309–2322, 2009. https://doi.org/10.1016/j.rser.2009.03.015
6. Kirubakaran et al., "A review on fuel cell technologies and power electronic interface," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 9, pp. 2430–2440, 2009. https://doi.org/10.1016/j.rser.2009.04.004
7. H. Choi et al., "Development and demonstration of PEM fuel-cell–battery hybrid system for propulsion of tourist boat," *International Journal of Hydrogen Energy*, vol. 41, no. 5, pp. 3591–3599, 2016. https://doi.org/10.1016/j.ijhydene.2015.12.186
8. K. M. Bagherabadi et al., "System-level modeling of marine power plant with PEMFC system and battery," *International Journal of Naval Architecture and Ocean Engineering*, vol. 14, 100487, 2022. https://doi.org/10.1016/j.ijnaoe.2022.100487
9. P. Xie et al., "A two-layer energy management system for a hybrid electrical passenger ship with multi-PEM fuel cell stack," *International Journal of Hydrogen Energy*, vol. 50, pp. 1005–1019, 2024. https://doi.org/10.1016/j.ijhydene.2023.09.297
10. J. I. Lee et al., "Analysis of solid oxide fuel cell hybrid power system in marine application for CO_2 reduction," *Energy Reports*, vol. 9, pp. 3072–3081, 2023. https://doi.org/10.1016/j.egyr.2023.01.123
11. W. Yu et al., "Evaluation on the energy efficiency and emissions reduction of a short-route hybrid sightseeing ship," *Ocean Engineering*, vol. 162, pp. 34–42, 2018. https://doi.org/10.1016/j.oceaneng.2018.05.016
12. Kravos et al., "Thermodynamically consistent reduced electrochemical model for PEM fuel cell," *Journal of Power Sources*, vol. 454, 227930, 2020. https://doi.org/10.1016/j.jpowsour.2020.227930
13. L. Barelli et al., "Dynamic modeling of a hybrid propulsion system for tourist boat," *Energies*, vol. 11, 2592, 2018. https://doi.org/10.3390/en11102592
14. B. L. Biert et al., "A review of fuel cell systems for maritime applications," *Journal of Power Sources*, vol. 327, pp. 345–364, 2016. https://doi.org/10.1016/j.jpowsour.2016.07.007
15. J. Penga et al., "Analysis of hybrid ship machinery system with PEM fuel cells and battery pack," *Applied Sciences*, vol. 14, 2878, 2024. https://doi.org/10.3390/app14072878

16. N. Shakeri et al., "Modeling and stability analysis of fuel cell-based marine hybrid power systems," *IEEE Transactions on Transportation Electrification*, vol. 10, no. 3, pp. 5075–5091, 2024. https://doi.org/10.1109/TTE.2023.3325579
17. C. Dall'Armi et al., "Hybrid PEM fuel cell power plants fuelled by hydrogen for shipping," *Energies*, vol. 16, 2023. https://doi.org/10.3390/en16042022
18. G. Elkafas et al., "Fuel cell systems for maritime: Review of research and applications," *Processes*, vol. 11, 97, 2022. https://doi.org/10.3390/pr11010097
19. J. Larminie and A. Dicks, *Fuel Cell Systems Explained*, 3rd ed., Wiley, 2017. https://doi.org/10.1002/9781118878330
20. P. Ghimire et al., "Dynamic modeling and control of marine DC hybrid power system," *IEEE Transactions on Transportation Electrification*, 2020. https://doi.org/10.1109/TTE.2020.3023896