DC Microgrid For Emulating Offshore Energy Systems

M. A. Hossain[1], N. A. Salam[1] and E. MacA. Gray[1]

Abstract—**Offshore energy systems present unique challenges, such as remote locations and highly variable renewable power generation. The integration of hydrogen technologies—including fuel cells and electrolysers—offers a promising solution to reduce dependence on diesel generators and lower CO_2 emissions in these isolated environments. This study presents novel voltage control strategies tailored for the dynamic operation of hydrogen-based DC microgrids, specifically designed to support aquaculture applications in ocean settings. A testbed using commercial DC/DC converters and programmable sources was developed to emulate real-world marine energy conditions. The proposed droop-based control system dynamically manages fuel cell output and electrolyser input based on DC bus voltage fluctuations, ensuring stable and efficient microgrid operation. Experimental results demonstrate high tracking accuracy, with R^2 values of 0.9836 for solar, 0.9494 for wind, and 0.9606 for wave generation. The DC link voltage was maintained within ±5 V of the nominal 380 V under load variations, validating the robustness and responsiveness of the controller. This approach supports reliable energy management and efficient hydrogen integration, providing a scalable and cost-effective solution for sustainable offshore energy systems.**

Keywords— **Hydrogen microgrid, fuel cells, electrolysers, voltage controller, renewable energy integration, DC power supply.**

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I. Introduction

IN today's power systems, the growing focus on sustainable and renewable energy sources is transforming the traditional energy landscape. Integrating renewables like solar and wind offers significant benefits, including cleaner energy and reduced environmental impact, but it also introduces challenges such as intermittency and unpredictability, complicating supply-demand balance, grid stability, and overall reliability. Managing energy flows within microgrids, especially with variable renewable inputs, demands advanced control algorithms to maintain stability [1]. These complexities call for innovative solutions to facilitate a smooth transition to sustainable energy systems. One promising solution is the use of hydrogen fuel cells and electrolysers within a DC environment, which can efficiently store excess energy generated during peak renewable periods as hydrogen. This hydrogen can then be used during low-generation periods, thus balancing variable renewable output with consistent energy demand. The integration of hydrogen technologies into power grids enhances flexibility and resilience, offering a dynamic energy storage solution that is particularly beneficial in microgrid applications such as DC microgrids on ships or in off-grid communities [2]. These technologies help to harness locally derived renewable energy sources, mitigating their variability and reducing reliance on environmentally harmful diesel. However, the efficient production and storage of hydrogen remain challenging, requiring electrolysers to operate dynamically, matching fluctuating energy inputs and demands while ensuring safe and reliable hydrogen storage [3].

Numerous studies have been conducted on the configuration, design, and optimisation of hydrogen microgrids. For instance, in [4], the development of an integrated energy system for sustainable aquaculture that combines renewable energy-based green hydrogen and oxygen production with electricity generation is explored. The optimal design of hydrogen-based storage in a hybrid renewable energy system, taking into account economic and environmental uncertainties is discussed in [5]. In [6], an integrated energy system that combines hydrogen fuel derived from a hybrid wind and solar system with diesel fuel to power buses is presented. Their optimisation of a photovoltaic and wind turbine-powered hydrogen refuelling system results in replacing 54% of diesel-fuelled buses with hydrogen-fuelled ones, leading to a 36% reduction in the standard deviation of levelized driving cost, a 46% decrease in the mean value of carbon intensity, and a 51% reduction in the standard deviation of carbon intensity, thus enhancing economic and environmental performance. An energy management strategy for a wind-hydrogen microgrid using hierarchical model predictive control for both long-term and short-term operations, aiming to optimise revenue and minimise operating costs, is proposed in [7]. Suitable inner controllers are designed in [8] to improve the stability of microgrid. In [9], a distributed economic model predictive control scheme is developed for a PV/Hydrogen DC microgrid that integrates energy management, economic optimisation, and power regulation to ensure power supply-demand balance, DC bus voltage stability, and economic efficiency, while also reducing computation burden and power oscillation compared to centralised control. The importance of renewable energy sources in microgrid-based Power- to-X (P2X) systems is highlighted in [10], identifying hydrogen storage as a financially viable alternative to batteries for high-power applications. These studies have been validated through computer simulations and/or hardware-in-the-loop (HIL) testing.

The findings in the existing literature are predominantly validated through computer simulations or hardware-in-the-loop (HIL) testing rather than industry-standard experimental setups. Sole reliance on simulations or HIL testing risks proposed solutions underperforming when applied in practical scenarios, resulting in a significant gap between theoretical results and actual field performance. To bridge this gap, Griffith University has developed a state-of-the-art DC Micro-grid experimental platform. This platform is designed to serve as a testbed for investigating the integration of diverse renewable energy sources, energy storage systems, and loads, with a particular focus on hydrogen-based energy storage for medium-to-long-term applications. By utilising this experimental platform, this study aims to tackle key challenges in renewable energy integration, energy storage, and microgrid operation, with the overarching goal of improving system resilience, reliability, and efficiency.

The paper is organised as follows. Section II presents an application scenario of a hydrogen DC microgrid in an aquaculture environment. In Section III, the mathematical modelling of microgrid components is derived for simulation purposes. The proposed voltage-based control architecture is developed in Section IV. In Section V, industry-standard experimental output is carried out to demonstrate the effectiveness of the proposed voltage control for microgrid reliable operation. The work is concluded in Section VI.

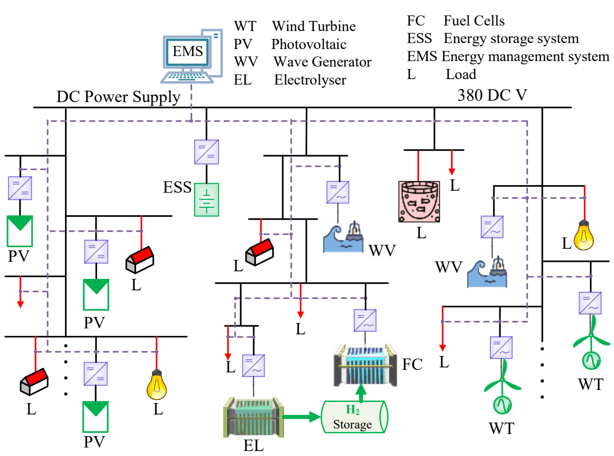


Fig. 1: Schematic of Islanded Hydrogen DC Microgrid (*Solid lines: electrical power flow; dashed lines: communication/control links*).

II. OVERVIEW OF HYDROGEN DC MICROGRID

The study aims to explore viable renewable energy solutions tailored for ocean environments, emphasizing the adoption of hydrogen DC microgrids as an optimal choice to power aquaculture facilities. These systems not only promote environmental sustainability but also foster economic growth, aligning with the United Nations Sustainable Development Goals (UN SDGs) that address issues such as food security and poverty alleviation [11].

Aquaculture activities are targeted in remote coastal areas abundant with ocean resources, as illustrated in Fig. 1. For healthy fish cultivation, Oxygen is a critical factor that is essential for the respiration of aquatic organisms. Adequate dissolved oxygen levels are necessary to support metabolic processes, growth, and overall health of the fish. Typically, dissolved oxygen levels should be maintained between 5-7 mg/L for optimal fish health, as lower levels can lead to stress, reduced feed intake, and increased susceptibility to diseases [12]. In aquaculture systems, oxygen can be supplied through various means such as aeration devices, oxygenation systems, and the natural photosynthesis of aquatic plants. However, in this project, Oxygen is produced as a byproduct during electrolysis process of electrolyser. Ensuring consistent and adequate oxygen supply not only promotes vigorous growth and high survival rates but also enhances the overall efficiency and productivity of fish farming operations.

The proposed microgrid configuration integrates various renewable energy sources strategically positioned on floating platforms. The design incorporates specific components to harness consistent ocean energy effectively:

- **Wind Turbines and Wave Generators:** Each contributing 1 kW, these systems capture kinetic energy from wind and waves, ensuring continuous power supply even in dynamic marine conditions. In this study, their outputs are emulated using KEPCO programmable 4-quadrant (bipolar) power supplies.
- **Solar Panels:** Generating 5 kW of electricity, these panels utilise abundant solar energy available in coastal regions to complement power generation. A 5 kW programmable DC power supply (B&K Precision) is used to simulate solar generation.
- **Energy Storage:** A 25.2 kWh Kokam battery bank provides short-term storage, stabilising energy supply against intermittent renewable sources and demand fluctuations.
- **Electrolysers:** With a capacity of 1.5 kW, electrolysers convert surplus electricity into hydrogen through electrolysis, enabling medium-to-long-term energy storage. Their operation is emulated using a programmable AC/DC ITECH 1.8 kW load.
- **Fuel Cells:** The 1 kW unit of a fuel cell converts stored hydrogen back into electricity when needed, enhancing grid resilience and ensuring uninterrupted power supply to aquaculture facilities. This is simulated using a 1 kW KEPCO programmable 4-quadrant (bipolar) power supply.
- **Loads:** The system includes critical aquaculture loads such as oxygenation systems for dissolved oxygen supply, water pumps for circulation and filtration, and lighting for fish habitat management. These are collectively represented and emulated using a programmable DC electronic load to reflect typical energy consumption patterns in aquaculture operations.

The microgrid was sized based on typical energy consumption patterns in small to medium-scale aquaculture operations, which generally require 10–20 kWh per day for systems including oxygenation, water circulation, feeding mechanisms, and lighting. Accordingly, the generation units—5 kW solar PV and 1 kW each for wind and wave sources—along with a 25.2 kWh battery and 1 kW fuel cell, were selected to ensure sufficient coverage for both daytime and backup energy needs under variable marine conditions.

In this study, a DC microgrid is used instead of an AC microgrids. One significant benefit is the reduction in energy losses. DC systems avoid the energy losses associated with AC-DC and DC-AC conversions, which can be as high as 5-10% each time energy is converted between AC and DC. By utilising a DC microgrid, these conversion losses are minimised, leading to higher overall system efficiency [13]. For instance, if a typical AC microgrid operates at 85-90% efficiency due to conversion losses, a DC microgrid can improve efficiency to around 95-98%. This efficiency gain is crucial in renewable energy applications where maximising the use of generated power is essential [14]. While specific cost savings depend on system scale and market conditions, the improved energy efficiency can lead to long-term operational benefits and reduced energy waste. Furthermore, DC microgrids are better suited for direct integration with renewable energy sources such as solar panels and batteries, which naturally produce and store DC power, thus simplifying system design and reducing costs. This streamlined integration can result in cost savings of up to 20% in system components and maintenance.

To evaluate the performance of the microgrid and guide control development, mathematical models of the key components—including fuel cells, electrolysers, and storage systems—are derived in the following section. These models form the basis for simulation and control system design.

III. HYDROGEN TECHNOLOGY MODELLING

A. Fuel Cells

Let H_{fr} be the extracted hydrogen flow rate from the storage. The fuel cell power output (P_{fc}) is calculated using the following model:

$$P_{fc} = \eta_{fc} \times H_{fr} \times E_h \quad (1)$$

where η_{fc} is the efficiency of the fuel cell (assumed to be 60% [15]) E_h is energy content of hydrogen (assumed to be 237,000 J/g).

B. Hydrogen Electrolyser Model

Let E_{ip} be the energy input in kilowatt-hours (kWh), η_{elz} be the efficiency of the electrolyser (assumed to be 70% [16]), U_{h2} be the energy density of hydrogen (33.33 kWh per kg of H_2), D_{h2} be the density of hydrogen at standard temperature and pressure (0.08988 kg per m^3).

The mass of produced hydrogen (H_{2p}) and its volume (V_{h2}) are calculated as follows:

$$H_{2p} = \frac{E_{ip} \times \eta_{elz}}{U_{h2}} \quad (2)$$

$$V_{h2} = \frac{H_{2p}}{D_{h2}} \quad (3)$$

The hydrogen production rate H_{2pr} is calculated based on the time interval (τ):

$$H_{2pr} = \frac{V_{h2}}{\tau} \quad (4)$$

C. Hydrogen Storage Model

Let $H_{2_{st,t+1}}$ be the storage level at time $t+1$, $H_{2_{pr}}$ be the rate of hydrogen production from electrolysers, $H_{2_{cr}}$ be the rate of hydrogen consumption by fuel cells, τ be the time step in seconds, and $H_{2_{st,maxC}}$ be the maximum storage capacity.

The storage level ($H_{2_{st,t+1}}$) is updated based on the difference between the production rate and consumption rate over the time step:

$$H_{2_{st,t+1}} = H_{2_{st,t}} + \left(H_{2_{pr}} - H_{2_{cr}}\right) \times \tau \quad (5)$$

The storage level is then constrained to not exceed the maximum capacity or go below zero:

$$H_{2_{st,min}} < H_{2_{st}} < H_{2_{st,max}}$$

The maximum storage capacity ($H_{2_{st,maxC}}$) is assumed to be 1000 units of hydrogen.

To operate these components, in the next section, the dynamic voltage controllers are proposed.

IV. Proposed Voltage Controller

This section outlines the control strategies developed to maintain efficient operation of the hydrogen DC microgrid. Emphasis is placed on the dynamic regulation of hydrogen flow rates, achieved through the implementation of droop controls. These controls are essential for managing the interactions between the electrolyser, fuel cell, and battery energy flows. By doing so, they significantly improve the resilience and reliability of the microgrid, particularly under challenging weather conditions.

A. *Dynamic Hydrogen Flow Rate Model*

Let K_v be the droop coefficient, V_{ref} be the reference voltage, and V_{meas} be the measured DC link voltage.

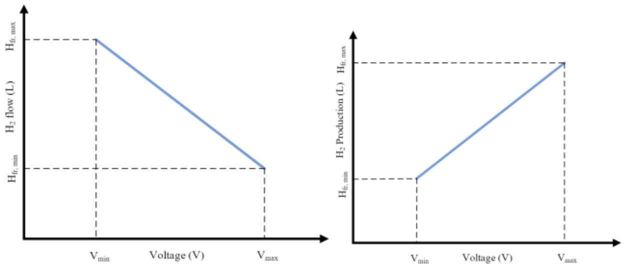
The hydrogen flow rate (H_{fr}) is calculated as follows:

$$H_{fr} = K_v \cdot (V_{ref} - V_{meas}) \quad (6)$$

This equation represents the linear relationship between the coefficient (K_v), the difference between the reference voltage (V_{ref}), and the measured DC link voltage (V_{meas}), providing a measure of the hydrogen flow rate that depends on power demands. This general Eq. 6 is used for both the operation of electrolyser and fuel cells, although the coefficient value will be different for both cases. For the electrolyser, K_v will be represented by K_{el}, and K_{fc} for the fuel cells. The coefficient can be determined by

$$K_v < \delta V / H_{fr,max} \quad (7)$$

where δV is deviated voltage from the reference value and $H_{fr,max}$ is the maximum hydrogen flow rate.



(a) (b)

Fig. 2: Voltage controls for (a) injecting hydrogen flow in fuel cells and (b) operating electrolyser

B. *The Operation of Fuel Cells and Electrolysers*

The principle of hydrogen flow to the fuel cells is illustrated in Fig. 2a. It shows that when the DC link voltage drops below the nominal voltage of 380V, such as 370V, the fuel cells will receive the maximum hydrogen flow to ensure the microgrid's reliability and stability. Conversely, when the DC link voltage is relatively high, such as 375V, the hydrogen flow decreases. This dynamic control of hydrogen flow is managed through droop control characteristics, with the slope determined by the system's physical constraints.

The hydrogen production rate of an electrolyser is directly related to its power consumption. When the electrolyser operates at maximum power, it produces the most hydrogen. To keep the DC link voltage within the desired range, the electrolyser's power consumption is dynamically adjusted. Fig. 2b demonstrates this control method. For instance, at a DC link voltage of 385V, the electrolyser produces less hydrogen due to lower power consumption. In contrast, at a higher DC link voltage of 390V, the electrolyser consumes more power to produce a greater amount of hydrogen. By adjusting power consumption in response to renewable power generation, the electrolyser helps maintaining stable microgrid operation by regulating the DC link voltage.

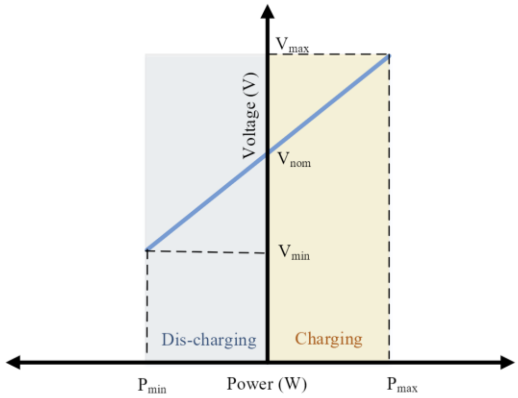


Fig. 3: Battery operational principles.

C. *Battery Control Strategy*

The operation of the microgrid heavily relies on the battery bank, and its role is described by the battery droop coefficient (K_b), a reference voltage (V_{ref}), and measured DC link voltage (Vmeas). The power supplied by the battery (P_b) is determined by the droop control equation:

$$P_b = K_b \cdot (V_{ref} - V_{meas}) \quad (8)$$

This equation dictates the necessary power adjustments to maintain the DC link voltage (V_{dc}) at the nominal level of 380 V. When V_{meas} exceeds V_{ref}, P_b is negative, indicating that the battery is charging to help stabilise V_{dc}. Conversely, when V_{meas} falls below V_{ref}, the battery discharges to uphold the nominal voltage of the DC bus. The battery bank continuously cycles between charging and discharging to maintain this nominal voltage, as shown in Fig. 3. The battery bank is a critical component of the microgrid system, ensuring reliable, secure, and resilient operation.

V. EXPERIMENTAL VALIDATION

This section showcases the effectiveness of the proposed control strategies in managing an islanded DC microgrid. Dynamic controllers have been implemented for fuel cells, electrolysers, and battery banks, allowing for adaptable microgrid operation. The battery control system is pivotal in maintaining reliable and secure microgrid functionality. The renewable energy generation data provided here represent typical patterns and can be readily customised for specific datasets. The bench-scale experiment for the hydrogen microgrid is illustrated in Fig. 4. The setup replicates the scenarios in Fig. 1: solar panels are represented by a 5 kW solar programmable power supply; wind and wave generators are each simulated using 1 kW programmable power supplies; and all loads are combined into a single programmable load.

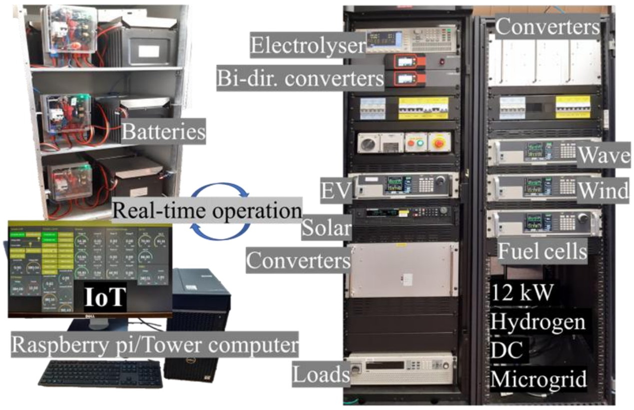
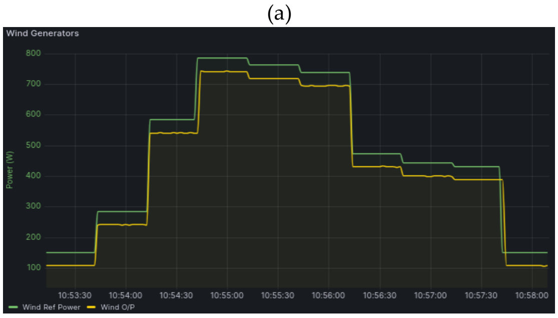


Fig. 4: Bench-scale experimental set up at Griffith University

(a)



(b)

(c)

Fig. 5: Power delivery tracking (a) solar PV (b) wind generator and (c) wave generator

(a)

(b)

Fig. 6: Operation of (a) Fuel cells and (b) DC link voltage

In the following sections, case studies to illustrate the effectiveness of the proposed control strategies are conducted. Each case study aims to showcase specific aspects of the microgrid's performance under various scenarios.

A. *Case Study 1: Power Generation Tracking*

This study examines the optimal transfer of power generated from renewable energy sources. A PI controller is utilised to manage the power flow in the DC/DC converter, providing a practical investigation of power transfer mechanisms and their fundamental principles. The results of the power tracking algorithms are shown in Fig. 5, indicating that the output powers of the converters closely match the reference powers from solar, wind, and wave generators. To evaluate the accuracy of these measurements, the R-squared and Mean Absolute Error (MAE) metrics are used. The R- squared value measures how well the regression model fits the observed data, with values closer to 1 indicating a better fit. MAE, on the other hand, quantifies the average deviation between the measured and reference values, with lower values representing higher accuracy.

For solar power, the R-squared is 0.9836 and the MAE is 72.49. The wind generator has an R-squared of 0.9494 and an MAE of 45.68. For the wave generator, the R-squared is 0.9606 and the MAE is 51.92. Comparing these R-squared values reveals that solar power achieves the highest goodness of fit (0.9836), followed by the wave generator (0.9606) and the wind generator (0.9494). This indicates that the PI controller for solar power offers the most precise power supply to the network, while the wind generator, despite having a slightly lower accuracy, still performs effectively. The superior performance of solar power in the power tracking results is primarily due to its higher rated capacity of 5 kW—five times greater than the 1 kW ratings of the wind and wave generators—resulting in a proportionally stronger influence on overall power delivery accuracy.

B. Case Study 2: Operation of Fuel Cells

This section focuses on the operation of fuel cells with the goal of maintaining a stable DC link voltage within specified limits to ensure the reliable and secure functioning of the microgrid. Under normal conditions, the fuel cells remain inactive. However, they automatically activate when power generation significantly exceeds or falls short of demand to ensure economical and reliable system operation.

When the fuel cells detect a lower DC link voltage, such as 375 V, due to insufficient power generation relative to demand, they are triggered. The operation of the fuel cells is shown in Fig. 6, illustrating transient power delivery in response to load variations. The fuel cells dynamically adjust their power output to accommodate changing power demands, operating at full capacity during periods of low power generation, which results in a low DC link voltage, as depicted in Fig. 6b.

C. Case Study 3: Operation of Electrolysers

This section examines the operation of the electrolyser, highlighting its role in maintaining the DC link voltage within defined limits for reliable microgrid operation. Fig. 7 illustrates the electrolyser's dynamic hydrogen production, showing how it adjusts based on the DC link voltage. Specifically, the electrolyser increases hydrogen production when the voltage is high (close to 390 V) and decreases production when the voltage is lower (around 385 V).

The detailed dynamics of the electrolyser's operation are presented in Fig. 7a. Due to the 4-second sampling interval of the electrolyser emulator, the damping power demand is not clearly captured. Fig. 7b further demonstrates that the electrolyser's operation is dependent on the DC link voltage. This voltage-responsive operation ensures that hydrogen production is aligned with the needs of the microgrid, thereby contributing to the system's overall stability.

Fig. 7: Operation of (a) Electrolyser and (b) DC link voltage

The robustness of electrolyser control under variable conditions is a key consideration in hydrogen-based microgrids. Electrolysers typically operate more efficiently and experience less wear when run under stable, continuous power input. To address this, the proposed droop-based control strategy includes rate-limit constraints that reduce the frequency and amplitude of input power fluctuations. This helps to prevent rapid on-off cycling and ensures smoother electrolyser operation, thereby preserving system longevity. Moreover, the control architecture is designed to coordinate the operation of multiple distributed energy resources during DC voltage deviations. Fuel cells are given priority during voltage dips to inject power rapidly and stabilise the bus, while batteries operate as primary short-term buffers. Electrolysers, in contrast, are used mainly during surplus generation periods and are curtailed first to prevent overvoltage. This layered and priority-based approach enables coordinated and resilient microgrid operation, effectively balancing reliability with component-specific operational constraints.

The experimental results clearly demonstrate the effectiveness of the proposed voltage control strategy, with accurate power tracking, coordinated resource operation, and stable DC bus voltage under varying conditions. These findings validate the practical feasibility and robustness of the control framework in managing hydrogen-integrated microgrids for marine applications.

D. Discussion

While this study demonstrates the effectiveness of voltage-based control strategies in managing hydrogen-integrated DC microgrids, the dynamic behavior of energy storage systems (ESS) and hydrogen subsystems introduces additional complexities that warrant further attention. In real-world applications, both batteries and hydrogen storage systems operate within strict capacity constraints—exceeding these limits can lead to performance degradation, safety risks, or operational shutdowns.

To account for this, our control framework incorporates logic-based safeguards. For example, if the battery reaches a full state of charge (100% SoC) while surplus renewable energy continues to be available, the system deactivates the electrolyser to prevent overproduction of hydrogen. Simultaneously, it redirects excess energy to critical loads or, if feasible, activates auxiliary loads (e.g., water filtration or backup lighting in aquaculture facilities). Conversely, when the hydrogen tank reaches its maximum capacity, further hydrogen production is halted, and surplus energy is diverted to battery storage or safely curtailed.

Consider a case where continuous high solar irradiance leads to extended overproduction during midday. If the battery is already at full SoC and the hydrogen tank is nearly full, the system must respond by reducing electrolyser input, gradually shedding non-critical loads, or signaling a need for demand-side response. These coordinated actions are essential to avoid over-voltage conditions and ensure microgrid stability.

Although these control responses are discussed at a rule-based level, the study does not yet include detailed real-time SoC modelling, electrochemical degradation mechanisms, or dynamic thermal behavior of storage systems. Integrating such models would allow for more predictive and adaptive control—e.g., modulating electrolyser operation based on real-time hydrogen consumption forecasts or accounting for degradation-aware battery dispatching. We recognise this as a limitation of the current work and propose it as a critical direction for future research to ensure robust, efficient, and scalable hydrogen microgrids in ocean-based and remote energy systems.

VI. Conclusion

This study introduces voltage control techniques for the dynamic operation of hydrogen DC microgrids in an ocean environment, enhancing their potential for industrial application and adoption. The effectiveness of these dynamic voltage controllers has been validated using commercial DC/DC converters. Experimental results demonstrate that the controllers designed for the hydrogen DC microgrid accurately track reference power with minimal error. This implies that the actual power output closely aligns with the reference power set by the controllers, ensuring efficient system operation and meeting the microgrid's energy demands effectively.

A key feature of the proposed controller is its ability to adjust the operation of fuel cells and electrolysers based on the DC bus voltage, influenced by variable ocean/renewable energy. When voltage levels deviate from the desired range, indicating either a surplus or deficiency of power, the controllers trigger the activation of fuel cells to generate additional power or electrolysers to produce hydrogen for storage. This adjustment ensures smooth operation and responsiveness to fluctuating energy demands, thereby optimising the microgrid's performance and reliability. These findings advance the adoption and implementation of hydrogen technologies in renewable energy systems, promoting sustainable and efficient energy solutions for applications such as aquaculture and beyond.

Future work will focus on integrating real-time weather forecasting and adaptive control algorithms to enhance the responsiveness of the hydrogen microgrid under rapidly changing environmental conditions. Additionally, the system will be scaled to support larger aquaculture operations and investigated within hybrid AC/DC microgrid architectures to evaluate broader applicability and performance.

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