International Journal of Hydrogen Energy 203 (2026) 153228

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

An enhanced predictive energy management of a green hydrogen integrated microgrid based on correlation analysis considering uncertain conditions

Jordan Isaac [a], Ahmed M.A. Haidar [a,b,*], Andreas Helwig [b]

[a] Department of Electrical and Electronic Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Malaysia
[b] School of Engineering, University of Southern Queensland, Toowoomba, Australia

ARTICLE INFO

Keywords:
Green hydrogen
Renewable microgrid
Predictive correlation
Fuel cells
Cloud-based IoT

ABSTRACT

The increasing adoption of renewable energy sources presents unique challenges due to their unpredictable nature and the need for efficient energy storage management. Maintaining grid stability requires robust energy storage solutions to manage the variability as the power industry shifts towards renewable generation. This paper focuses on developing a reliable model based on experimental predictive correlation for a green hybrid grid-integrated microgrid that utilizes hydrogen storage to mitigate energy fluctuation. The goal is to maintain frequency and voltage stability across various operating scenarios using hydrogen as the primary energy storage system. A comprehensive framework is presented for modelling a hybrid energy system that combines solar, hydrogen storage, fuel cells, and lithium battery storage. The initial step in this study involves experimental investigation to formulate a predictive correlation index (PCI) for hydrogen-based energy systems, concentrating on the relationship between hydrogen flowrate, pressure, temperature, and the resulting electrical outputs, voltage, and current. This formulation is then used to develop an enhanced energy management coordination strategy based on the correlation index, leveraging the capabilities of model predictive control to anticipate fluctuations in energy demand and supply. A cloud-based Internet of Things (IoT) platform is utilized to monitor system performance in real-time under various conditions, manage storage efficiently, and enhance security by minimizing vulnerabilities. Numerical findings confirm that the hybrid predictive scheme reduces frequency deviation within ±0.16 % and constrains voltage variation to approximately ±4 %. Here, the experimental PCI values identify an optimal hydrogen operating range of 0.3–0.4 bar for reliable performance. Performance benchmarking further demonstrates that, compared with conventional droop-based methods reported in earlier studies, the proposed correlated hybrid control strategy achieves improved transient response and lower steady-state error, ensuring more reliable coordination of hydrogen and battery storage. The results prove that the proposed predictive coordination strategy effectively mitigates voltage and frequency fluctuations during transient situations by optimally controlling the hydrogen storage within the microgrid. This outcome underscores the positive impact of the proposed predictive coordination strategies in enhancing continuous power supply and improving the overall efficiency of grid-integrated systems.

1. Introduction

Global warming and pollution issues have been worsening due to the release of greenhouse gases into the Earth's atmosphere. The primary source of greenhouse gas emissions is the burning of fossil fuels, like coal, oil, and natural gas, which release carbon dioxide (CO2). Due to the widespread use of fossil fuels, the world today experiences a scarcity of natural resources. Depletion of natural resources has become a major driver behind the increased adoption of renewable energy, such as solar energy, hydropower, and wind energy, in today's technology. Consequently, energy storage based on green hydrogen technology emerges as a promising solution for the power and utilities industry to reduce pollution and improve the integration of renewable generation in on or off-grid microgrids [1]. The increasingly complex power grid has raised

This article is part of a special issue entitled: Green Cities (Ramadan) published in International Journal of Hydrogen Energy.

* Corresponding author. Department of Electrical and Electronic Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Malaysia.
E-mail addresses: ahahmed@unimas.my, ahmed.haidar@unisq.edu.au (A.M.A. Haidar).

https://doi.org/10.1016/j.ijhydene.2025.153228
Received 2 August 2025; Received in revised form 8 December 2025; Accepted 24 December 2025

concerns about instability, as heavily loaded transmission lines could result in widespread voltage collapse incidents, leading to substantial national losses [2]. The primary challenge lies in managing the inherently unpredictable nature of renewable energy resources (RER) and their storage capacity. Microgrids that integrate renewable energy sources play a crucial role in maintaining a balance between generation and demand, and enhancing grid resilience, efficiency, and sustainability. However, integrating RER can introduce voltage and frequency fluctuations that potentially disrupt grid stability. The central theme of the current studies revolves around strategically incorporating energy storage systems to meet the power management requirements of microgrids. In the context of modern power grids, this involves intelligent integration of hydrogen-based energy storage systems. These systems should operate in harmony with the existing centralized control infrastructure of conventional power grids, highlighting the shift towards energy-efficient hydrogen production. This transition involves complementing traditional battery energy storage systems with fuel cell storage systems powered by renewable electrolysis [3]. Effective management of grid-integrated renewable generation, especially when combined with green hydrogen energy storage, requires optimal control strategies, including parameter-matching techniques as proposed in this paper. The coordinating operation of power converters is crucial for achieving optimum and reliable management of grid-integrated renewable generation, particularly when green hydrogen energy storage systems are involved. In complex energy systems such as those with multiple power sources and green hydrogen storage, optimal control strategies are crucial for efficient operation. Specifically, where power sources are interconnected at a point of common coupling, a dynamic predictive coordination control strategy based on model predictive control (MPC) theory is essential for effective energy management [4]. The study advocates the use of energy storage to mitigate voltage and frequency variations caused by fluctuating renewable energy resources. Mainly, this involves leveraging energy storage systems, such as electrolyzers for hydrogen production, to mitigate voltage and frequency issues within the microgrid environment [5]. This localized approach empowers microgrids to autonomously manage renewable energy variability by producing and utilizing hydrogen energy storage through strategic switching of electrolyzers.

The existing review studies, summarized in a hypothetical Table 1, establish a solid foundation for the current research by directly addressing the crucial aspects of hydrogen storage integration and advanced control in microgrid systems. As the integration of hydrogen storage systems within hybrid microgrids becomes a topic of growing interest, several studies and research efforts have explored the modelling and analysis of these systems, offering valuable insights and contributions to the field. In particular, the integration of hydrogen storage systems into hybrid microgrids has attracted significant research interest, with several studies offering innovative solutions to key challenges. For instance, an enhanced MPC with virtual synchronous generator control is proposed in Ref. [6] to address the power imbalances caused by load switching in microgrids. The authors incorporated adaptive inertia damping and weight coefficient adjustments to improve frequency and voltage stability under low-inertia conditions. The study in Ref. [7] applied the MPC method to address poor active power sharing in hybrid AC/DC MGs under high AC load demands, outperforming conventional droop controllers in overload scenarios. In Ref. [8], the authors focused on coordinated control for hybrid energy storage systems in DC microgrids using a two-layer continuous MPC. This approach can ensure State of Charge (SOC) consistency and reduce DC bus fluctuations. Meanwhile [9], proposed stochastic MPC-based fault-tolerant strategies for real-time microgrid operation using tree-based and chance-constrained approaches. A combination of control strategies, particularly through smart microgrid technologies, can enhance power grid stability to withstand fluctuations in renewable energy sources and equipment malfunctions. The study in Ref. [10] developed predictive power control for grid-connected photovoltaic (PV) systems with energy

Table 1
Comparison of the paper's main contributions with the related recently published studies.

Ref.	Description and Control Method	Conclusion	Limitation
[6]	*Microgrids (Wind, PV, DG)* *Model predictive control based on virtual synchronous generator (frequency)*	*Limiting frequency fluctuations to a safe range*	*The proposed control scheme may require complex implementation and tuning.* *The proposed method's effectiveness under varying operating conditions and system configurations needs further validation through extensive experimental testing.*
[7]	*Hybrid AC/DC microgrid* *Model predictive control and Droop control (frequency, power, voltage, THD)*	*Outperformance in terms of steady-state overload power sharing, transient overload damping, nonlinear load harmonic attenuation, and integral time absolute error analyses*	*The simulation results need validation through real-world testing to assess the proposed controller's performance in practical scenarios.* *The scalability and applicability of the proposed controller to diverse hybrid AC/DC microgrid configurations require further investigation.*
[8]	*DC microgrid (PV, hybrid energy storage system)* *Continuous control set model predictive control*	*Reduce DC bus fluctuations.* *Achieve a consistent battery SOC faster.*	*The proposed control strategy may face challenges in real-time implementation due to computational complexity and hardware constraints.* *The performance of the control strategy under dynamic and uncertain operating conditions needs to be evaluated comprehensively*
[9]	*Microgrid* *Chance-constrained MPC*	*Optimize the utilization of renewable energy sources while maintaining a balance between self-sufficiency and grid interaction*	*The effectiveness of the fault-tolerant strategy module in addressing complex fault scenarios and system reconfigurations requires further validation in real-world environments.* *The computational complexity associated with stochastic MPC approaches may limit their real-time implementation in large-scale microgrid systems.*
[10]	*Grid-connected PV system (PV, ESS)* *Model predictive power control (MPPC)*	*Flexible power regulation* *Maintaining stable DC and AC voltages*	*The proposed scheme needs validation through real-world deployment to assess its performance under diverse operating conditions and grid environments.* *The scalability and adaptability of the MPPC scheme to different PV-ESS system configurations and grid architectures require further investigation.*
[11]	*Islanded and grid-connected microgrid (Wind, H2 storage)* *Hierarchical MPC*	*Hydrogen device degradations caused by the switching states, such as start-up, shutdown,*	*The hierarchical MPC-based EMS may encounter challenges in real-time*

(continued on next page)