Energy Proceedings
Vol 53, 2025
ISSN 2004-2965

Development of a Hydrogen-based Microgrid Test Bench with Level of Hydrogen Estimator#

Zhipeng Hou[1], Fengxiang Chen [2*], Yafeng Guo [1], Huitao Zhang[2], Su Zhou [3]

1 Department of Control Science and Engineering, Tongji University, Shanghai 201804, China
2 School of Automotive Studies, Tongji University, Shanghai 201804, China
3 Shanghai Zhongqiao Vocational and Technical University, Shanghai 201514, China
(Corresponding Author: fxchen@tongji.edu.cn)

ABSTRACT

The hydrogen-based microgrid is an excellent solution to address the issue of curtailment caused by the intermittency of renewable energy sources. In such a system, the energy management system plays a crucial role in determining the operational status of the microgrid. To effectively verify the energy management strategies, a hydrogen-based microgrid test bench has been developed, which mainly includes photovoltaic (PV) panels, a programmable direct current (DC) power supply, loads, a lead-acid battery, and a hydrogen storage system. The lead-acid battery is directly connected to a DC bus, primarily serving as short-term storage to address instantaneous power imbalances and maintain bus voltage stability. The hydrogen storage system includes a PEM water electrolysis (PEMWE) system, metal hydride tank, and a PEM fuel cell (PEMFC) system, serving as long-term storage for seasonal energy storage. Considering that the level of hydrogen (LOH) is crucial parameter for the energy management strategy, an LOH estimator, which is used to estimate the hydrogen capacity in the metal hydride tank, has been proposed. This study aims to bridge the gap between simulation and practical application, providing valuable insights and tools for the development of hydrogen-based microgrid system.

Keywords: hydrogen-based microgrid, hydrogen storage system, energy management strategy, LOH estimator

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
MHSHC	Metal Hydride Storage Hydrogen Capacity
DC	Direct Current
PEMWE	Proton Exchange Membrane Water Electrolysis
PEMFC	Proton Exchange Membrane Fuel Cell
LOH	Level of Hydrogen
SOC	State of Charge
ESS	Energy Storage System
HSS	Hydrogen Storage System
Symbols	
N	Number of cells
F	Faraday constant

1. INTRODUCTION

The large-scale generation of renewable energy has significantly outpaced the current grid's capacity to fully absorb it. This has led to substantial amounts of wind and solar power being discarded, resulting in frequent occurrences of "wind curtailment" and "solar curtailment." Despite the vast potential of renewable energy, its actual supply to end-users remains relatively low.

The microgrid system[1], as an efficient and innovative solution, is fundamentally comprised of distributed energy systems, advanced energy storage devices, and diverse load demands. Energy storage system (ESS) can flexibly switch between acting as an "energy source" and a "load," releasing or storing energy to maintain the balance between electricity supply and demand. There are numerous types of energy storage technologies, each with its unique characteristics[2], primarily categorized into short-term and long-term storage. Short-term storage, exemplified by batteries, quickly responds to instantaneous power fluctuations, while long-term storage focuses on inter-seasonal energy allocation. Hydrogen storage, with its high energy density, environmental friendliness, and zero-emission characteristics, has attracted significant attention. To efficiently utilize both types of storage units, detailed energy management strategies need to be developed.

The energy management strategy (EMS) is central to the operation of microgrids and must be customized

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

based on the characteristics of the system components and their integration. It specifies the power settings for each component, aiming for optimal performance: meeting the load requirements, optimizing energy storage, enhancing efficiency, reducing costs, and achieving overall optimization. Nehri et al.[3] provided a comprehensive summary of the design approaches and energy management strategies for hybrid renewable energy systems, beginning with system configuration and proceeding to a detailed explanation of three control structures and their respective energy management strategies. Conversely, Bajpai et al.[4] concentrated on off-grid hybrid renewable energy systems, with a primary focus on optimizing component sizing and the modeling process, as well as a thorough discussion of the critical factors and methods involved in formulating energy management strategies. Vivas et al.[5] initially outlined the components and integration methods of microgrid systems, followed by a detailed discussion of the technical and economic specifications and operational standards for commonly used components. Building on this foundation, they systematically classified and summarized energy management strategies, addressing the diversity and complexity of energy management objectives. These work have demonstrated that the energy management strategies of microgrid systems are deeply influenced by both their intrinsic research characteristics and the system component composition and integration methods.

An introduction to existing hydrogen energy microgrid projects and test platforms is provided in reference[6]. Valverde et al.[7] from the University of Seville proposed the design of hydrogen energy microgrids and energy management strategies. Building on this approach, a test platform for hydrogen energy microgrid systems was established to study the impact of energy management strategies on system performance. Given the crucial role of energy storage status in energy management, estimation modules for state of charge (SOC) and level of hydrogen (LOH) were included. This setup allows for more effective validation of various energy management strategies.

The main structure of the paper is as follows: Section 2 introduces the hydrogen energy storage microgrid system. Section 3 discusses the capacity calculation of the energy storage system. Section 4 and 5 provides a discussion and a summary.

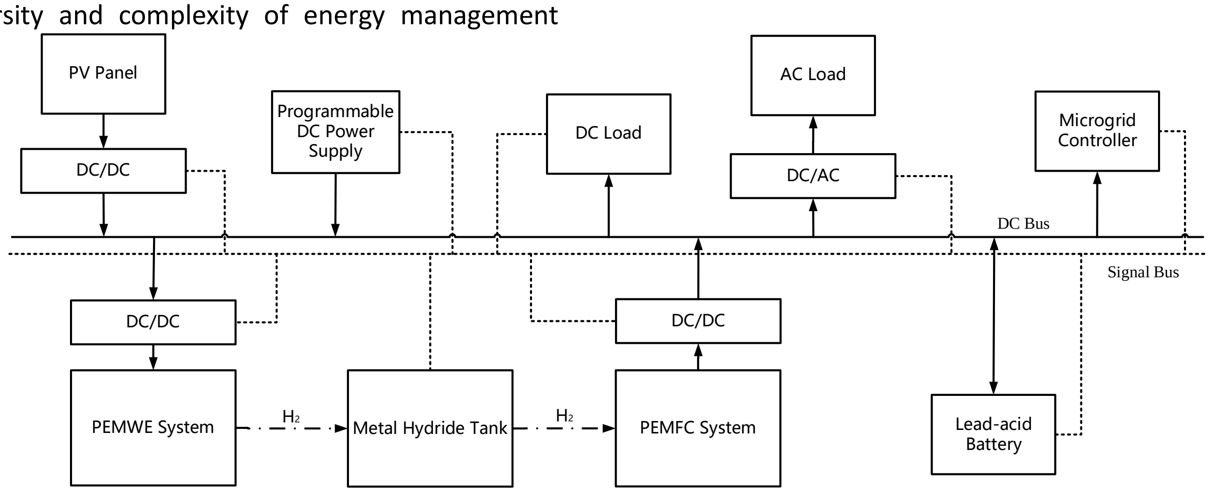

Fig. 1 Hydrogen-based microgrid test bench schematic diagram

2. HYDROGEN MICROGRID SYSTEM

2.1 Composition of hydrogen microgrid system

To validate the capability of the system components for off-grid operation, the topology shown in *Fig. 1* was sampled. photovoltaic (PV) panels, connected to the direct current (DC) bus via a DC-DC converter, serves as the primary power source within the system to meet the load demands. The programmable DC power supply accurately simulates the solar power generation curve, ensuring comprehensive testing of the system under conditions of no sunlight. When there is a power imbalance between solar energy and the load, the ESS, which includes lead-acid batteries and hydrogen storage system (HSS), adjusts flexibly to ensure stable operation of the system. The HSS mainly includes a PEM water electrolysis (PEMWE) system, metal hydride storage tanks, and a PEM fuel cell (PEMFC) system. The PEMWE and PEMFC system are connected to the DC bus via DC-DC converters. When excess electricity is available, it can be supplied to PEMWE system through the DC-DC converters, converting the electricity into hydrogen and storing it in the metal hydride storage tanks for later use in the PEMFC system. To meet the average power demand of 50 W, the microgrid test bench is as shown in *Fig. 2*, and the parameters of the components in the small hydrogen energy microgrid system are listed in Table 1.

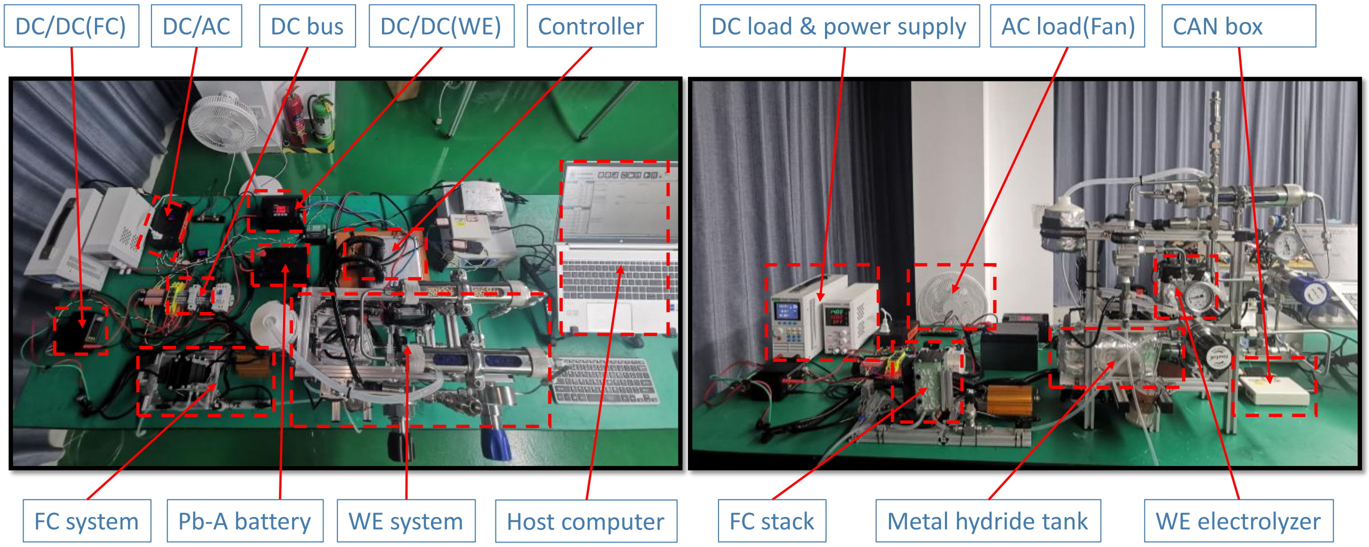

Fig. 2 Hydrogen-based microgrid test bench (Left: Top View, Right: Front View)

Table 1 Details of the components in the hydrogen-based microgrid system

System component	Specifications
Load	Average 50 W, peak 100 W
PV panel	150Wp@1000W/m^2
Programmable DC electronic load & power supply	0-150W
Lead-acid battery	12V, 12Ah
PEMWE	100W@22A, 2cells*30cm^2
PEMFC	60W@5.5A, 18cells*14cm^2
MHSHC	200NL H_2
DC bus voltage	12V (depend on battery)

2.2 Control structure of the hydrogen energy microgrid system

The PV panels utilize an efficient Maximum Power Point Tracking (MPPT) control technique to maximize their output power, while the microgrid controller focuses on seamlessly switching between the solar panels and the programmable DC power supply to accommodate changes in energy supply. The system employs a non-intervention strategy for the load, only monitoring changes in the load current. In the hydrogen energy microgrid, the PEMWE and PEMFC systems become the focal points of regulation, with the lead-acid battery quietly maintaining bus power balance and voltage stability. The system adopts a hierarchical control architecture; the supervisory layer intelligently plans energy management, setting power targets for the electrolyzer and fuel cell, while the local control layer accurately executes these plans, ensuring both follow the target power outputs closely. This hierarchical framework, as shown in *Fig. 3*, demonstrates the advanced control logic of the hydrogen-based microgrid.

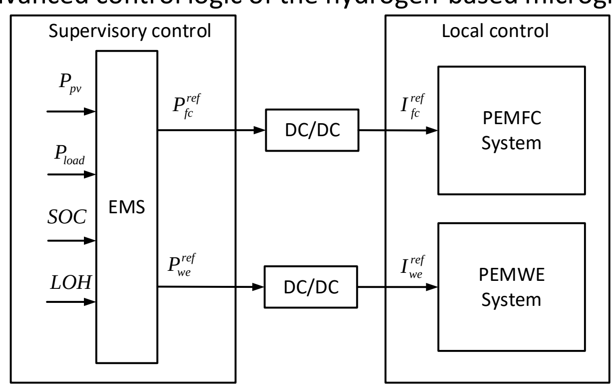

Fig. 3 Hierarchical control framework for the hydrogen-based microgrid

3. ENERGY STORAGE SYSTEM CAPACITY

3.1 Metal hydride hydrogen storage tank capacity

The LOH is an important variable in the energy management strategy of the hydrogen-based microgrid system. First, the initial value of LOH is determined using the Pressure-Temperature-Concentration (PTC) curve, as shown in *Fig. 4*. The LOH is calculated by Equation (1).

$$LOH(k+1) = LOH(k) + \frac{(\dot{n}_{ele}^{prod} - \dot{n}_{fc}^{cons})T_s}{V_{H_2}} \tag{1}$$

where $\dot{n}_{ele}^{prod}$ and $\dot{n}_{fc}^{cons}$ are the hydrogen production rate of the electrolyzer and the hydrogen consumption rate of the fuel cell, respectively, NL/s, while V_{H_2} represents the hydrogen storage capacity of the metal hydride storage tank, NL.

$$\dot{n}_{ele}^{prod} = \frac{N_{ele} I_{ele}^{ref}}{2F} V_m \qquad (2)$$
$$\dot{n}_{fc}^{cons} = \frac{N_{fc} I_{fc}^{ref}}{2F} V_m$$

where N_{ele} and N_{fc} represent the number of cells in the electrolyzer and the fuel cell, respectively, and V_m is the molar volume of the gas at standard conditions, 22.4 NL/mol.

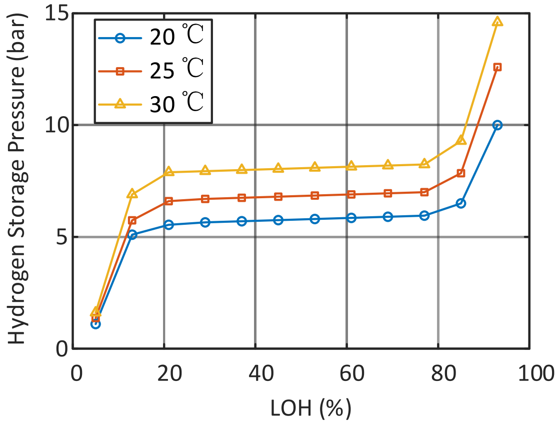

Fig. 4 PTC curve of the metal hydride storage tank [8]

3.2 Lead-acid battery energy storage capacity

Similarly, the SOC of the lead-acid battery is also an important variable in the energy management strategy of the hydrogen-based microgrid system. Initially, the initial value of SOC is obtained based on the relationship between capacity and open-circuit voltage, as shown in *Fig. 5*. Then, the SOC is calculated by Equation (3).

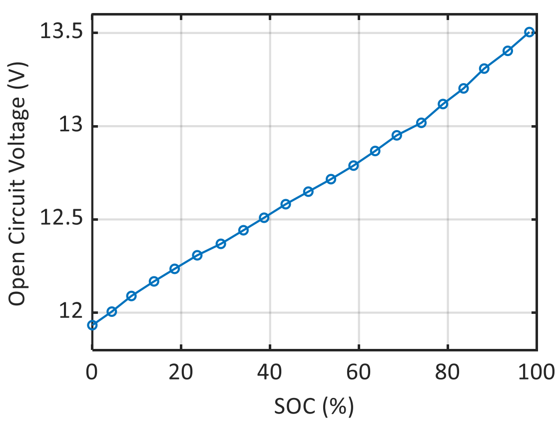

Fig. 5 The relationship between battery SOC and open-circuit voltage

$$SOC(k+1) = SOC(k) + \frac{(I_{bat}^{char} - I_{bat}^{disc})T_s}{I_{bat}^{nomi}} \qquad (3)$$

where I_{bat}^{char} and I_{bat}^{disc} represent the charging and discharging currents of the lead-acid battery, respectively, and I_{bat}^{nomi} is the nominal capacity of the lead-acid battery.

4. DISCUSSION

The hydrogen-based microgrid test bench in this study demonstrates significant flexibility, supporting both grid-connected and off-grid operation modes. In grid-connected mode, the test bench can seamlessly interface with the main grid, ensuring stability and reliability of power supply. In off-grid mode, it can achieve self-sufficiency without relying on the main grid, providing an effective solution for specific scenarios where independent power supply is required. The design strategy of directly connecting the battery to the bus significantly reduces the complexity of the control system. This design minimizes intermediate conversion stages, enhancing overall system efficiency and response speed, while ensuring the stability of the bus voltage.

Moreover, this study proposes a method for estimating the storage state of the energy storage system. However, it is noteworthy that the initial storage state determined by the proposed method may not be accurate due to the insensitivity of lead-acid battery voltage and metal hydride storage pressure to capacity.

Additionally, it is important to note that the current design of the test bench does not comprehensively cover all possible extreme conditions. Specifically, the system may face challenges when the energy storage system is insufficient and ssolar power generation cannot meet the load demand, or when the energy storage system is full and solar power generation continues to be excessive. If not properly managed, these extreme conditions could adversely affect the stability and economic efficiency of the system.

Finally, it should be emphasized that although the current hydrogen-based microgrid test bench is primarily aimed at small-scale systems (e.g., sustaining a load of around 50W), its design principles and core technologies are highly scalable and transferable. With appropriate scaling and technical adjustments, this test bench has the potential to become an effective platform for validating energy management strategies for medium and even larger hydrogen-based microgrid systems, thereby providing strong support for the widespread application of hydrogen-based microgrid technology.

5. SUMMARY

This study underscores the pivotal role of hydrogen-based microgrids in mitigating the curtailment issues caused by the intermittency of renewable energy sources. By developing a comprehensive test bench that includes photovoltaic panels, a programmable DC power supply, various loads, a lead-acid battery, and a hydrogen storage system, we have created a robust platform for evaluating and refining energy management strategies. The lead-acid battery's direct connection to the DC bus ensures immediate response to power imbalances, thereby maintaining voltage stability. Meanwhile, the hydrogen storage system, which incorporates a PEM water electrolysis system, a metal hydride tank, and a PEM fuel cell system, provides a reliable solution for long-term, seasonal energy storage.

A significant contribution of this research is the introduction of a LOH estimator. This tool is crucial for accurately determining the hydrogen capacity within the metal hydride tank, thereby optimizing the overall energy management strategy. The LOH estimator enhances the operational efficiency and reliability of the microgrid, making it a vital component for practical applications.

In conclusion, this study bridges the gap between theoretical simulations and real-world applications, offering valuable insights and practical tools for the development of hydrogen-based microgrid systems. The findings not only advance our understanding of hydrogen storage dynamics but also contribute to the broader objective of integrating renewable energy sources into stable and efficient power systems. This research lays a solid foundation for future innovations in energy management and storage technologies.

ACKNOWLEDGEMENT

This work is supported by International Exchange Program for Graduate Students, Tongji University.

REFERENCE

[1] Lasseter RH. MicroGrids. IEEE Power Eng. Soc. Winter Meet.2002; 1:305-8.

[2] Tan KM, Babu TS, Ramachandaramurthy VK, Kasinathan P, Solanki SG, Raveendran SK. Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration. Journal of Energy Storage. 2021 Jul 1;39:102591.

[3] Nehrir MH, Wang C, Strunz K, et al. A Review of Hybrid Renewable/Alternative Energy Systems for Electric Power Generation: Configurations, Control, and Applications[J]. IEEE Transactions on Sustainable Energy, 2011; 2(4): 392-403.

[4] Bajpai P, Dash V. Hybrid renewable energy systems for power generation in stland-alone applications: a review[J]. Renewable and Sustainable Energy Reviews. 2012; 16(5):2926–39.

[5] Vivas FJ, De-las-Heras A, Segura F, et al. A review of energy management strategies for renewable hybrid energy systems with hydrogen backup[J]. Renewable and Sustainable Energy Reviews. 2018; 82: 126-155.

[6] Schucan T. Case studies of integrated hydrogen systems. International energy agency hydrogen implementing agreement, final report for subtask a of task 11-integrated systems. International Energy Agency Hydrogen Implementing Agreement, Golden, CO (US), Task 11 (US); 1999 Dec 31.

[7] Valverde L, Rosa F, Bordons C. Design, planning and management of a hydrogen-based microgrid. IEEE transactions on industrial informatics. 2013 Feb 12;9(3):1398-404.

[8] Dhaou H, Askri F, Salah MB, Jemni A, et al. Measurement and modelling of kinetics of hydrogen sorption by LaNi5 and two related pseudobinary compounds. International journal of hydrogen energy. 2007 Apr 1;32(5):576-87.