Renewable Energy, Environment, and Power Quality Journal (REE&PQJ)
ISSN:3020-531X
Volume 26, July 2026

Control of an Islanded PV–Battery–PEM Electrolyser Microgrid for Green Hydrogen Production

A. Llamazares, S. Martín-Arroyo, J. A. Cebollero and M. García-Gracia

Department of Electrical Engineering
EINA, Zaragoza University
María de Luna 3 – Edificio Torres Quevedo – Campus Río Ebro –50018 Zaragoza (Spain)

Abstract.

This paper presents the design and control of an islanded PV–battery–PEM electrolyser microgrid for green hydrogen production. The system integrates a PV plant, a lithium-ion BESS, and a 425 kW PEM electrolyser. A hierarchical control strategy is proposed, combining local converter control, DC-bus voltage regulation and a supervisory layer including cloud classification, fault handling and maximum-power operation modes.

The system is modelled in MATLAB/Simulink and evaluated under representative scenarios such as cloud transients, PV faults, maximum-power operation and battery cycling. Results show that the proposed control maintains DC-bus stability within acceptable limits, ensures compliance with electrolyser ramp-rate constraints (10% of nominal power per second), and avoids undesirable power oscillations. The BESS effectively acts as spinning reserve, enabling continuous hydrogen production during short disturbances and safe operation under fault conditions.

Key words. Off-grid hybrid system, grid stability, power plant control.

1. Introduction

Hybrid systems combining renewable sources and energy storage are a key solution to supply isolated loads and new applications such as hydrogen production [1]. Green hydrogen produced by water electrolysis using renewable electricity is a promising option to decarbonize industry and transport, but it requires careful integration of electrolysers into power systems subject to intermittent generation. Among low-temperature electrolysers, Proton Exchange Membrane (PEM) technology offers fast dynamic response, compactness and high purity hydrogen, making it appropriate for coupling with fluctuating PV generation [2].

In islanded microgrids for hydrogen production, the PEM electrolyser behaves as a large, dynamically sensitive load whose power profile must respect minimum-power thresholds, ramp-rate limits and auxiliary power requirements to avoid accelerated degradation. Fast and frequent changes in current, voltage, temperature and pressure due to renewable variability can lead to significant aging of the membrane, catalyst and bipolar plates. Therefore, the plant control must smooth the impact of renewable fluctuations and coordinate the use of BESS as spinning reserve [3]. The plant control strategies have been designed based on the technical limitations of the electrolyser.

2. System Description

A. Microgrid Topology

The microgrid, shown in Fig. 1, consists of a 700 V DC bus [4] and a 400 V three-phase AC bus. The DC bus connects a 728 kWp PV plant through a boost DC/DC converter, a lithium-ion 973.2 kWh BESS through a bidirectional buck–boost DC/DC converter and a 425 kW PEM electrolyser. The AC bus supplies 75 kW of auxiliary systems of the electrolyser (pumps, compressors, heaters, etc.) and other consumptions through a grid-forming inverter, which links both buses in islanded operation. Corresponding to the Balance of Plant (BoP).

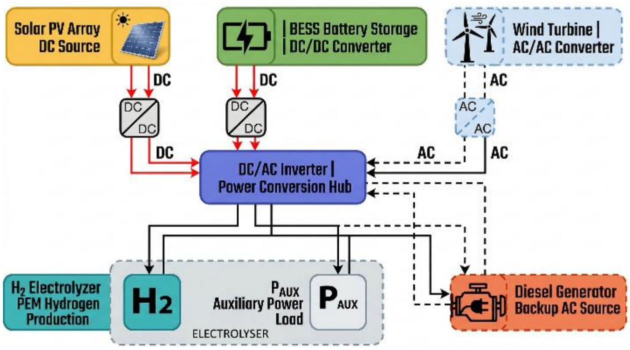


Fig. 1. Overall structure of the islanded PV–BESS–PEM electrolyser microgrid.

B. PEM Electrolyser Electrical Model

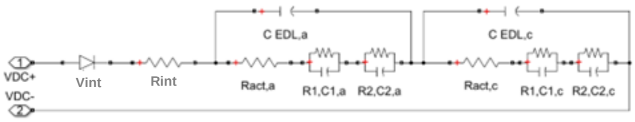
The electrolyser stack consists of 292 cells in series and 119 branches in parallel, delivering 425 kW nominal DC power. Its dynamic behaviour is represented by an equivalent circuit (Fig. 2) comprising a reversible voltage source ($\boldsymbol{V}_{\text{int}}$), an ohmic resistance ($\boldsymbol{R}_{\text{int}}$) and two RC branches modeling activation and diffusion phenomena at anode and cathode.

$$V_{\text{cell}} = V_{\text{int}} + I_{\text{cell}} R_{\text{int}} + f(I_{\text{cell}}, t) \quad (1)$$

where $\boldsymbol{f(I_{\text{cell}}, t)}$ represents the transient voltage contribution of the RC branches. In steady-state, the stack voltage can be approximated as:

$$V_{\text{stack}} \approx N_{\text{s}}(V_{\text{int}} + I_{\text{cell}} R_{\text{eq}}) \quad (2)$$

where $\boldsymbol{N_s}$ is the number of series cells and $\boldsymbol{R_{eq}}$ is an equivalent resistance [5].



V_{rev}	1.377 V	$C_{EDL, a}$	1.93 F
R_{ohm}	0.1025 Ω	$R_{act, c}$	0.025 Ω
$R_{act, a}$	0.05 Ω	$R1_{, c}$	0.005 Ω
$R1_{, a}$	0.01 Ω	$C1_{, c}$	100 F
$C1_{, a}$	100 F	$R2_{, c}$	0.0025 Ω
$R2_{, a}$	0.005 Ω	$C2_{, c}$	10 F
$C2_{, a}$	10 F	$C_{EDL, c}$	1.93 F

Fig. 2. Simulink electrolyser electrical model and parameter values for a PEM cell.

C. Battery and Spinning Reserve Sizing

The Battery Energy Storage System (BESS) is designed to act as spinning reserve (SR), while the synchronous generator is reserved for emergency backup and its use is minimised. The plant control system periodically estimates the SR requirements based on demand and electrolyser constraints, ensuring stable operation under renewable variability and fault conditions. The BESS must be capable of supporting transient generation losses, maintaining minimum electrolyser operation, supplying auxiliary loads, and enabling safe shutdown.
Accordingly, the required BESS capacity is determined by:

$$\boldsymbol{E_{BEES}} > \boldsymbol{E_{stab}} + \boldsymbol{E_{prod,min}} + \boldsymbol{E_{shutdown}} + \boldsymbol{E_{cold}} \quad (3)$$

where $\boldsymbol{E_{stab}}$ represents the energy required to compensate short-term renewable fluctuations, $\boldsymbol{E_{prod,min}}$ ensures minimum electrolyser operation, $\boldsymbol{E_{shutdown}}$ guarantees safe shutdown, and $\boldsymbol{E_{cold}}$ accounts for standby operation. This sizing ensures that the BESS can maintain DC-bus stability and protect the electrolyser from abrupt power variations.

3. Microgrid Operational Requirements

The proposed microgrid must satisfy the following operational requirements:

R1 – Cloud disturbance management.
The electrolyser must maintain its power setpoint during short cloud passages, while reducing its production when cloud coverage persists for more than 30 s. A weather-forecast module estimates the expected PV generation, while a cloud-classification algorithm distinguishes between transient and persistent cloud events. This approach allows hydrogen production to follow the available renewable power while avoiding unnecessary oscillations caused by short-duration clouds.

R2 – Fault-tolerant operation.
The microgrid must operate safely under abnormal conditions such as overloads, short circuits or overvoltages in the PV plant or its converter. In the simulations, the specific fault type is not modelled; instead, a protection signal indicates whether the protection system has tripped.

R3 – Maximum-power operation mode.
The electrolyser must be capable of operating at nominal power independently of PV generation when required by the operator for technical or economic reasons. In this mode, the battery supplies the additional energy, subject to the maximum operating time defined in the battery sizing.

R4 – Battery support and spinning reserve.
The battery must compensate short-term irradiance drops due to cloud passages and ensure the operation of auxiliary systems in case of PV faults. It must also support the minimum electrolyser production level, defined as 5 % of nominal power, and enable safe shutdown if necessary.

R5 – Battery operating limits.
To minimize degradation, the battery operates within a state-of-charge range of 20–80 %. These limits are considered in the battery sizing and control strategy.

R6 – Maintain DC bus stability within ±3%.

4. Microgrid Control

The control architecture is hierarchical, with local converter controls and a supervisory layer that manages electrolyser operation modes based on available renewable power, PV faults and operator commands. The DC-bus voltage reference is used as an indirect control variable to regulate the electrolyser power, exploiting the nonlinear V–I characteristic of the electrolyser.

The control system is organized hierarchically to keep the DC bus stable and to protect the PEM electrolyser against PV variability. Within the supervisory layer, the control system distinguishes between short-term clouds (duration < 30 s), where the battery compensates the PV deficit to maintain constant hydrogen production, and long-term cloud events, where the electrolyser power is reduced in 5% steps until a new steady-state is reached.

In addition, PV faults trigger a minimum-power mode (5% of nominal power) supplied by the battery, with safe shutdown if the SoC falls below a threshold. A maximum-power mode is also implemented, allowing the electrolyser to operate at rated power using the BESS as spinning reserve, while always respecting ramp-rate and SoC constraints.

The system is organised as a DC microgrid comprising a photovoltaic (PV) plant, a battery and an electrolyser, governed by a hierarchical control scheme implemented as Simulink function blocks (Fig. 3). At the second lowest level are the local converter controllers. The PV plant's DC/DC boost converter uses a cascaded structure with an outer DC-bus voltage loop and an inner current loop, both PI-controlled and with different bandwidths (the voltage PI is slower than the current PI) to avoid conflicts in determining the duty cycle and to keep the bus as stable as possible. In this configuration, MPPT is not used, DC-bus voltage stability is prioritised over maximum power extraction. The battery's bidirectional DC/DC converter is controlled with voltage loops in buck mode (discharge) and boost mode (charge), again using PI regulators, and it supplies (or absorbs) whatever power is required to maintain the DC-bus voltage reference.

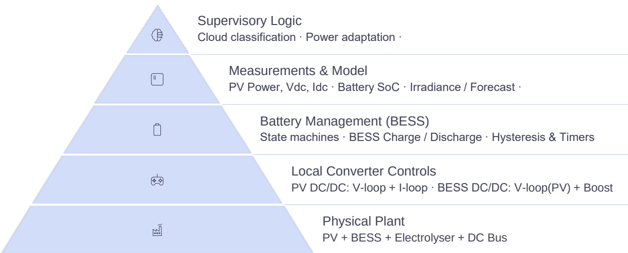


Fig. 3. Hierarchical control architecture: Multi-level control scheme for PV + BESS + Electrolyser system.

Above these local loops, a **state-machine layer** supervises the battery operating mode. A first state machine decides whether the battery should be **charging, discharging or idle**, based on the state of charge (SoC), the DC-bus voltage and the battery power, incorporating hysteresis and a minimum delay (0.5 s) between transitions to prevent rapid, unstable switching. A second logic block enables or disables the battery depending on the deviation between the measured voltage and a computed "available" voltage, and on the SoC, again with hysteresis and a start-up timing filter to reject initial transients:

$$\boldsymbol{If\ V_{bus} < 0.95\ p.u.\ or\ SoC\ < 80\% \Rightarrow enable}$$
$$\boldsymbol{If\ V_{bus} > 1.05\ p.u.\ and\ I_{load} < 0.5\ A \Rightarrow disable}$$

At the Measurement & Model level, the microgrid controller computes the DC-bus voltage reference $\boldsymbol{V_{disp}}$ from the available renewable power, the auxiliary consumption and a simplified electrolyser model (diode plus series resistance):

$$V_{disp} = V_{Int} + I \cdot R_{eq} \qquad (4)$$

Where I is the current that must flow through the electrolyser to achieve the desired power, obtained from the available renewable power after subtracting the electrolyser auxiliaries: $P_{PV-Wind} - P_{Aux}$.

At a higher level, the main controller classifies irradiance variations using cloud detection (irradiance drop) and a weather-forecast. It distinguishes between short cloud events (where the battery sustains production) and prolonged overcast conditions (where electrolyser power is reduced in 5% steps every 30 s). A ramp-rate limiter is also applied to avoid or minimise PEM degradation due to rapid production changes [6]. This issue is even more critical for SOECs (Solid Oxide Electrolysis Cells) [7].

The scheme is completed with two special modes: PV fault operation, which drives the electrolyser to its minimum safe operating point (5% production) while the battery SoC remains above 20%; below this SoC threshold, a safe shutdown is executed. The second is a maximum-power mode, which fixes $\boldsymbol{V_{disp}}$ at 1 p.u. so that the electrolyser operates at rated power. Overall, this yields a coherent architecture in which the PV plant, battery and electrolyser are coordinated through state logic and voltage/power setpoints, with the explicit aim of preserving electrolyser lifetime and using the battery as an intelligent spinning reserve equivalent.

5. Results and discussions

Four main scenarios are considered to evaluate the proposed control, implemented in MATLAB/Simulink:

Scenario 1: Cloud passages
Short- and long-duration clouds are imposed on the irradiance profile (see Fig. 4) to test cloud classification, power adaptation and BESS transient support (Fig. 5).

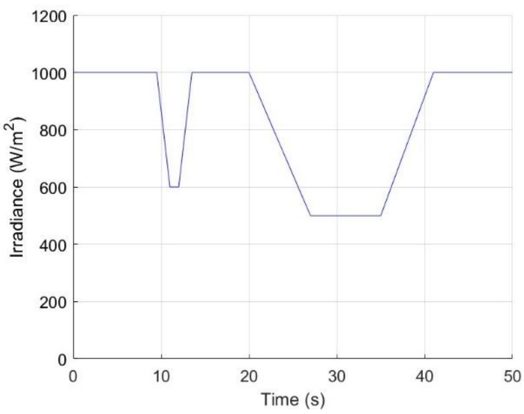


Fig. 4. Irradiance profile of Scenario 1.

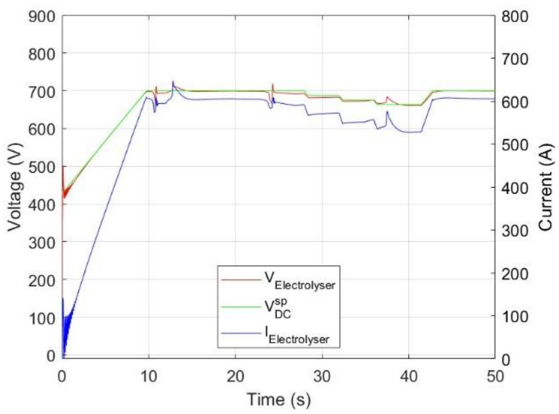


Fig. 5. Electrolyser voltage and current, and voltage reference V_{disp} in Scenario 1.

When PV generation decreases and the control system identifies the event as a persistent cloud, hydrogen production is reduced by lowering the DC bus voltage. Conversely, if the irradiance drop is classified as a short-term cloud, the battery compensates the power deficit, maintaining stable hydrogen production and avoiding undesirable fluctuations. To evaluate this behaviour, the irradiance profile shown in Fig. 4 includes both a short cloud event between 9.5 s and 13.5 s and a long-duration cloud between 20 s and 41 s.

Scenario 2: PV fault

A disconnection and reconnection of the PV plant has been simulated to test minimum-power operation and safe ramp-up.

When a fault is detected, the electrolyser switches to minimum production mode (5% of nominal power), supplied by the battery. Once the fault is cleared, the PV plant is reconnected and the system returns to its original operating state, considering the electrolyser ramp-rate limitation of 10% of nominal power per second. To simulate this scenario, the irradiance remains constant at 1000 W/m².

Scenario 3: Maximum-power mode

This scenario evaluates the performance of the control system when the maximum-power mode is activated. The transition from normal operation to maximum production is analysed under a worst-case condition, where the electrolyser output increases from 5% to 100% of nominal power following a prolonged PV production drop. The ramp-rate limitation of 10% of nominal power per second is enforced throughout the process, while irradiance is 1000 W/m². Fig. 6 shows the results obtained.

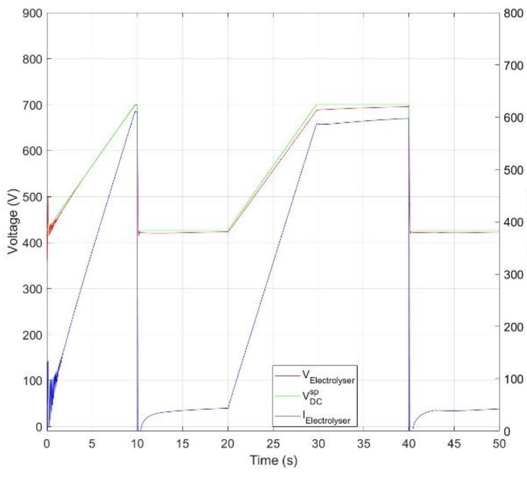


Fig. 6. Electrolyser voltage and current, and voltage reference $\boldsymbol{V_{disp}}$ in Scenario 3.

Scenario 4. Battery charging.

The battery charge–discharge control is also evaluated by simulating a scenario in which the BESS state of charge falls below 80% and is subsequently recharged. To induce the discharge, a cloud event is applied. The analysis focuses on the impact of this process on the DC bus stability and the electrolyser operation.

Several studies indicate that these variations in current and voltage accelerate the degradation of the electrolyser. Therefore, a second control strategy has been developed to operate at constant power, allowing slow variations to adapt to the available renewable energy. This second strategy also demonstrates improved overall plant efficiency.

6. Conclusions

This paper presents a hierarchical control strategy for an islanded PV–BESS–PEM electrolyser microgrid aimed at green hydrogen production. The proposed control effectively coordinates renewable generation, battery storage and electrolyser operation under variable and uncertain conditions.

Simulation results demonstrate that the system maintains DC-bus stability, respects electrolyser operational constraints and minimises unnecessary power fluctuations. The DC-bus voltage deviation remains below ±3%, and ramp-rate constraints are always respected. Furthermore, no instability or control saturation was observed in any scenario.

The cloud classification strategy successfully distinguishes between short and long disturbances, allowing optimal use of the BESS as spinning reserve. Furthermore, the system ensures safe operation under PV fault conditions and supports maximum-power operation when required.

Overall, the proposed approach improves system robustness, enhances operational flexibility and contributes to reducing electrolyser degradation, making it suitable for real-world off-grid hydrogen production systems.

7. References

[1] X. L. Yan and R. Hino, Nuclear Hydrogen Production Handbook. Boca Raton, FL, USA: CRC Press, 2011.

[2] X. Lu, B. Du, S. Zhou, W. Zhu, Y. Li, Y. Yang, C. Xie, B. Zhao, L. Zhang, J. Song, and Z. Deng, "Optimization of power allocation for wind-hydrogen system multi-stack PEM water electrolyzer considering degradation conditions," Int. J. Hydrogen Energy, vol. 48, no. 15, pp. 5850–5872, 2023.

[3] Martín-Arroyo, S., Cebollero, J.A., García-Gracia, M., Llamazares, Á., "Stand-alone hybrid power plant based on SiC solar PV and wind inverters with smart spinning reserve management", Electronics, vol. 10, no. 7, 2021.

[4] Llamazares A., Garcia-Gracia M., Martin-Arroyo S, "Characterization of Parasitic Impedance in PCB Using a Flexible Test Probe Based on a Curve-Fitting Method", IEEE Access, vol. 22, no. 6, pp. 40695 - 40705, 202. doi: 10.1109/ACCESS.2021.3064190.

[5] A. M. De Corato, M. Ghazavi Dozein, S. Riaz, and P. Mancarella, "Hydrogen Electrolyzer Load Modelling for Steady-State Power System Studies," IEEE Trans. Power Del., vol. 38, no. 6, pp. 4312–4323, Dec. 2023, doi: 10.1109/TPWRD.2023.3315749.

[6] M. Sánchez et al., "Assessing Fluctuating Wind to Hydrogen Production via Long-Term Dynamic Modelling of Electrolyzers," Applied Energy, 2024.

[7] J. Zhang et al., "Degradation of Solid Oxide Electrolysis Cells," J. Mater. Sci. Technol., vol. 55, pp. 35–55, 2020.