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Grid ancillary services using electrolyzer-Based power-to-Gas systems with increasing renewable penetration

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A B S T R A C T

Increasing penetrations of renewable-based generation have led to a decrease in the bulk power system inertia and an increase in intermittency and uncertainty in generation. Energy storage is considered to be an important factor to help manage renewable energy generation at greater penetrations. Hydrogen is a viable long-term storage alternative. This paper analyzes and presents use cases for leveraging electrolyzer-based power-to-gas systems for electric grid support. The paper also discusses some grid services that may favor the use of hydrogen-based storage over other forms such as battery energy storage. Real-time controls are developed, implemented and demonstrated using a power-hardware-in-the-loop(PHIL) setup with a 225-kW proton-exchange-membrane electrolyzer stack. These controls demonstrate frequency and voltage support for the grid for different levels of renewable penetration (0%, 25%, and 50%). A comparison of the results shows the changes in respective frequencies and voltages as seen as different buses as a result of support from the electrolyzers and notes the impact on hydrogen production as a result of grid support. Finally, the paper discusses the practical nuances of implementing the tests with physical hardware, such as inverter/electrolyzer efficiency, as well as the related constraints and opportunities.

1. Introduction

Increasing renewable penetrations are changing electric power systems (EPS) operations. The intermittent output from distributed energy resources (DERs) can induce temporal and geographic variations. It affects system power quality as frequency and voltage disturbances. At the bulk level, increased inverter-based DER (IBDERs) generation reduces system inertia. It can lead to more severe oscillations, causing instability and higher reserve requirements. Operators might enforce power ramp-rate requirements for fewer frequency oscillations [1]. At the distribution level, mechanical devices help manage reactive power and regulate system voltage levels. With high penetration levels of renewable IBDERs, voltage fluctuations can significantly increase tap operations [2–4]. It affects both operating costs and grid reliability.

Renewable firming, declining system inertia, and frequency/voltage disturbances are often addressed by utilities. They either curtail active DER power output and use flexible storage [5] or use fast controllable power reserves. Battery energy storage systems (BESS) [6–8] and power-to-gas (P2G) systems [9–15] are among the most promising applications for grid support. They offer load flexibility. A detailed review will be discussed in Section 2. At present, the use of BESS does not scale well in terms of cost-benefit for large-scale applications. Value-stacking opportunities and diverse markets might offer P2G a more sustainable business case over time. P2G systems can couple electrical systems with other energy systems and provide reliable long-term storage solutions. Electrolyzers produce hydrogen (H_2) from water using electricity and can be coupled with their applications in the growing fuel cell markets. Electrolyzers, especially proton-exchange-membrane (PEM) compared to alkaline electrolzyers, can ramp power consumption in a subsecond time resolution and are highly controllable [16]. This makes them ideal for grid services. Further, the H_2 thus produced can be consumed commercially or stored for an extended period [17]. Being nontoxic and lighter than air, H_2 is much safer to handle and use than most other fuels today [18]. It also dissipates rapidly in the air.

Therefore, this paper reviews existing work in P2G using H_2 for grid applications. It presents use cases for using electrolyzers in bulk and distribution EPS for grid services. The paper presents typical test cases for disturbances in system frequency and voltage following common events. It demonstrates control approaches based on power-hardware-in-the-loop (PHIL) using electrolyzers to support the grid during these

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disturbances. The test setup uses high-fidelity electromagnetic transient (EMT) and electromechanical power system models. It combines real-time dynamic controls and commercial electrolyzer systems with H_2 generation. PHIL integrates a 225-kW electrolyzer system in real-time with simulated power systems using EMT models. The experiments validate that electrolyzers can act upon receiving fast and slow dispatch commands to aid system frequency/voltage.

The remainder of this paper is organized as follows. Section 2 discusses the interaction between P2G systems and the electric grid. It discusses ongoing research on grid support using controllable storage and loads. Section 3 discusses the model of an electrolyzer as a controllable load. It discusses respective controllers for frequency and voltage support of power systems. Section 4 presents power system models, PHIL setup, and use cases for studying improvements in frequency and voltage using electrolyzers. Sections 5 and 6 discuss salient results from PHIL studies and respective challenges with practical implementation. Section 7 concludes the paper.

2. Literature review

This section provides a detailed review of the literature on Power-to-Gas (P2G) technology and its significance for power systems. P2G refers to the process of converting surplus electrical power into a gaseous fuel [19]. This is achieved by using electricity to convert water (H_2O) into hydrogen (H_2) and oxygen (O_2) through an *electrolyzer*. There are three broad classifications of electrolyzers: alkaline-based, proton-exchange-membrane (PEM) based, and solid-oxide (SO) based. PEM electrolyzers are the most suited for dynamic operations and will be the focus of this paper [20]. Based on this review, Fig. 1 provides an overview of the challenges and opportunities for P2G systems for grid-support services.

2.1. Significance of power-to-Gas for power systems

The increasing variability and intermittency associated with higher renewable energy penetrations have made the electric grid more

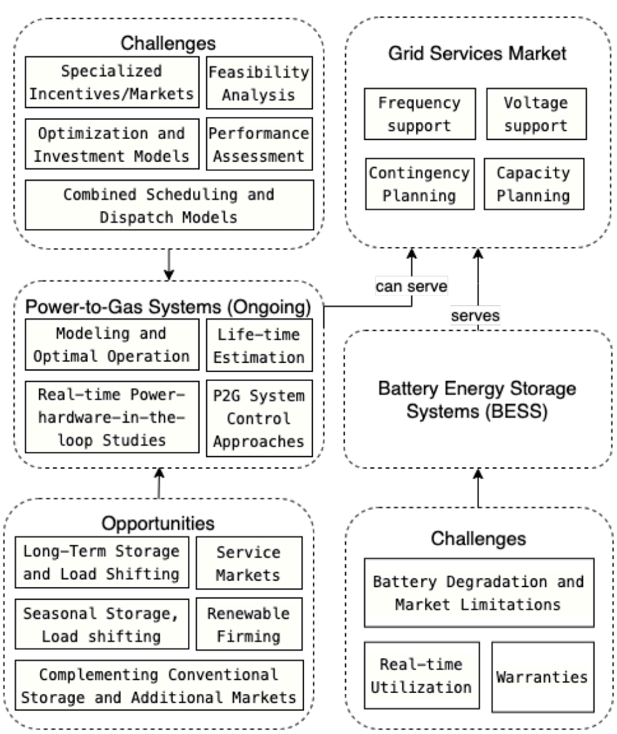

Fig. 1. Summary: Literature Review - Comparing Opportunities and Challenges of P2G Systems for Grid Services.

sensitive to disturbances. As a result, there is a growing need to actively improve grid stability. This has led to the development of reserve/demand management strategies to support the electric grid. Two major technologies sought for grid support are Battery Energy Storage Systems (BESS) and P2G. This section reviews the literature on the interaction between P2G systems and power systems for system frequency and voltage support. It also discusses the key advantages of P2G over BESS and highlights the novelty proposed in this paper.

2.1.1. Frequency support

Primary frequency response is critical for ensuring the reliability of bulk energy systems [21]. This response is determined locally and activated within cycles of changes in frequency. It can help stabilize abnormal frequency and reduce its impact on the bulk energy system. When generators respond to a frequency change, their governors speed up or slow down to counteract the imbalance (Fig. 2). Extreme events can induce severe oscillations in generator speed. In this paper, we demonstrate that electrolyzers can synchronize their load changes using frequency oscillations to reduce system imbalance. The electrolyzer response will help reduce the arrest period for smaller frequency deviations (Fig. 2) and actively participate during the rebound period to more quickly damp oscillations (Section 5). The control can be achieved using local frequency measurements to help stabilize grid frequency (Section 3).

2.1.2. Voltage support

At the distribution level, the intermittent nature of Distributed Energy Resources (DERs) can lead to severe voltage fluctuations. Changing PV penetration levels and intermittent cloud cover can cause sudden power imbalances [22]. These short-lived fluctuations in daytime distribution voltage profiles can translate into increased excessive operations for Load Tap Changers (LTCs) and voltage regulators [2–4]. Electrolyzers can respond to changes in DER output by ramping in the same direction, helping reduce voltage fluctuations. The control can be centralized or distributed based on the output from the DERs.

2.2. BESS For grid support

BESS is a fast-acting reserve that can support the grid with great versatility. Many researchers have proposed means and strategies to use BESS to support the grid at both distribution and bulk levels[23]. proposes a decision-making strategy to deploy BESS across the distribution grid. In [6–8], researchers considered various use cases to improve integration of DERs with the bulk grid using BESS. For example, [24] proposed a synergistic control using hybrid storage technologies to address power oscillations. BESS is often used to optimize the DER mix with energy storage in distribution systems [25–27].

Capacity degradation of storage cells is subject to usage patterns, chemistry, surrounding conditions, capacity, and other factors. Given the variability in these factors and evolving battery chemistries, battery degradation estimation is not well understood. As a result, storage

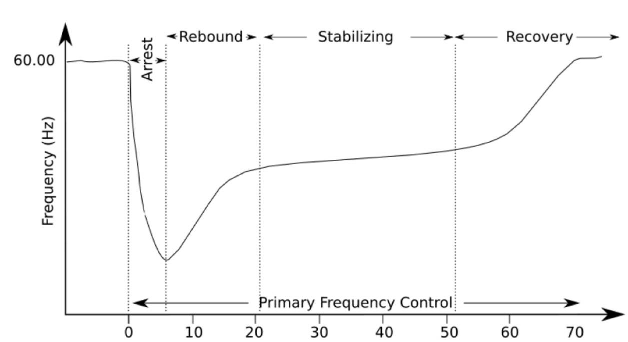

Fig. 2. Frequency response following a loss of generation [21].

manufacturers only support warranties under certain use cases. From a market standpoint, there is a lack of markets uniquely suited for services that only battery storage can provide. A lot of these markets have evolved around conventional generators [28]. Federal Energy Regulatory Commission Order 755 requires compensation that reflects the quality of service provided [29]. Also, using frequency reserves to smooth DER variability can increase the cost of large-scale integration of DERs [30]. Therefore, [30] used BESS to improve wind power predictability using renewable firming. These limitations make it difficult to develop a business case for large-scale BESS deployment.

In the present scenario, P2G systems do not benefit from specialized incentives and markets. However, P2G systems have existing markets beyond the electric grid. Hydrogen can be produced when there is excess renewable energy available and then transported to where it is needed or stored for later use. This helps to address the issue of intermittency in renewable energy generation and enables greater integration of renewables into the energy mix. The ability to transport and store gas-based fuels gives them a unique value-stacking opportunity. Thus, P2G systems are gaining traction for electric grid support. Next, we discuss the ongoing research in these applications for the electric grid.

2.3. Power-to-Gas systems for grid support

Research for P2G applications in the electric grid focuses on system design and market and operational use cases [9–15]. There is ongoing research on using existing infrastructure for multiple energy sources[9]. focuses on optimizing multi-carrier energy systems cost[10]. developed investment models that coordinate gas-electric systems[11]. proposed a stochastic approach to capture uncertainties in system loads, DER outputs, energy prices, and fuel cell operating conditions.

From an operational standpoint, some researchers focus on long-term storage and/or load shifting for the electric grid [31–38] and renewable firming using fuel cells [39]. At an aggregate level, [12] modeled P2G as a seasonal storage option[13]. proposed a two-layer optimization approach to manage P2G facilities via dynamic distribution pricing[14]. analyzed the energy share in Nordic countries and a plan toward fully renewable generation with DERs and storage options through conventional gas and P2G[15]. presented a feasibility analysis for P2G in the future Swiss low-voltage grid with intermittent DER generation. Hydrogen offers a space-efficient long-term means to store energy and reduce the impact of renewables variability on electricity prices. In [33,35,38], the authors proposed optimal scheduling methods using a combined P2G and gas-fired power plant. In [34,36], a similar study was done to propose an economic dispatch model that incorporates wind power, P2G facilities, and BESS. In [37], the authors demonstrated P2G systems performance in the Danish electricity spot market. P2G systems complemented conventional storage and offered support for additional markets.

2.4. Research opportunities for power-to-Gas systems

Most research in P2G applications has not focused on real-time utilization of P2G systems for dynamic power system support. However, fast controllable loads such as electrolyzers can provide these services. A detailed review [40] discussed the state of P2G applications for modeling and operation optimization. Many application areas can benefit from local optimization control of the P2G system[40]. highlighted that existing research has been mostly limited to power conversion or energy storage modeling. There is a need for work on flexible control and P2G participation in energy systems during normal operations and contingencies.

This paper outlines first-of-its-kind research using real-time PHIL studies with a 225-kW electrolyzer to quantify grid support benefits using electrolyzers with real-time controls. The next section discusses the electrolyzer control approaches developed for this research.

3. Grid support using electrolyzers

The fast response of electrolyzers allows their use for frequency/voltage support to the grid. This section presents the model using electrolyzers as controllable load and control strategies for frequency and voltage support. For voltage support, a centralized control infrastructure is assumed. Frequency support assumes localized control.

3.1. Electrolyzer as a controllable load

Electrolyzers can act as controllable DC loads integrated into the AC grid using inverters. They can adjust their demand in less than 1-second [16] and can be modeled as controlled-current sinks. Fig. 3 presents the connection topology and resulting equivalent circuit of an electrolyzer behind an inverter. The electrolyzer is a current-driven controlled load behind the power-electronic interface. Therefore, it is modeled as a controlled current source in the power system model.

3.2. Droop-Based frequency response using electrolyzers

At the transmission level, different areas might not share the same system frequency during disturbances. A frequency droop-based dispatch of electrolyzers can be used for fast frequency response. The controller equation is based on the Type 2 droop characteristics defined in [41] (fig. 4). Equations (1) and (2) and Algorithm 1 present the mathematical formulation for simulations.

$$m_{droop} = \frac{Frequency\_Response\_Capacity}{Frequency\_Response\_Band} \tag{1}$$

$$\delta P_{EL} = m_{droop} \cdot \left(f_{sys} - \left(f_{ref} \pm DB\right)\right)$$

$$P_{EL} = P_{f_{ref}} + m_{droop} \cdot \left(f_{sys} - \left(f_{ref} \pm DB\right)\right) \tag{2}$$

Unlike voltage control, the frequency can be measured locally. It can help the bulk system with frequency response independent of external references.

3.3. Ramp-Rate-Based voltage response using electrolyzers

In general, the ramp-rate limits imposed on PV power plants with energy storage-based firming are given by: (3).

$$\left|\frac{dP_{ESS}}{dt} + \frac{dP_{PV}}{dt}\right| \le RRate.\frac{P_{PVrated}}{60sec} \tag{3}$$

Here, *RRate* represents maximum ramp-rate limits. For example, in Germany and Puerto Rico, it is 10% per minute of rated PV power [1]. $RRate = \frac{10}{100}$ is used for the control equation (4). P_{PV} is output power (generation) and $P_{electrolyzer}$ is input power (load). When PV output increases, the electrolyzer load is temporarily increased to reduce the up ramp of P_{PV} and vice versa.

$$sgn\left(\frac{dP_{electrolyzer}}{dt}\right) = -sgn\left(\frac{dP_{PV}}{dt}\right) \tag{4}$$

where sgn(x) is the signum function.

Therefore, when DERs are paired with controllable loads, such as electrolyzers, the modified ramp-rate limits based on (3) are given as (5):

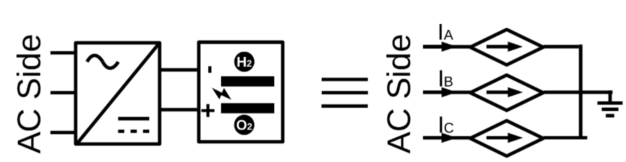

Fig. 3. Equivalent controlled-current source model: electrolyzer.

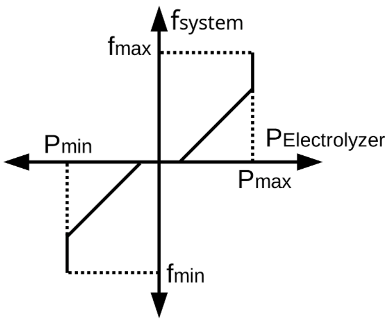

Fig. 4. Type 2 droop characteristics [41].

$$\left| -\frac{dP_{EL}}{dt} + \frac{dP_{PV}}{dt} \right| \leq \frac{10}{100} \cdot \frac{P_{PVrated}}{60sec} \tag{5}$$

Upon solving (5), the limits on the electrolyzer power P_{EL} at any time 't' are obtained. There are (6,7). They define the respective controller logic (Algorithm 2).

$$-\frac{10}{100} \cdot \frac{P_{PVrated}}{60sec} \leq -\frac{dP_{EL}}{dt} + \frac{dP_{PV}}{dt} \leq \frac{10}{100} \cdot \frac{P_{PVrated}}{60sec}$$

Integrating both sides for one time step δt and rearranging:

$$-\frac{10}{100} \cdot \frac{P_{PVrated}}{60sec} . \delta t + \delta P_{PV} + P_{EL_{t-\delta t}} \leq P_{EL_t} \tag{6}$$

$$P_{EL_t} \leq \frac{10}{100} \cdot \frac{P_{PVrated}}{60sec} . \delta t + \delta P_{PV} + P_{EL_{t-\delta t}} \tag{7}$$

The controller output is fed to the physical electrolyzer using analog inputs. The same output (scaled by capacity) controls the array of electrolyzer models simulated in the HIL. This emulates control of the entire fleet.

4. Experimental setup

The PHIL setup for grid support using electrolyzers includes a 225-kW electrolyzer stack, a grid simulator, and a real-time HIL platform. These models the electric grid and controllers.

4.1. The electrolyzer stack

Fig. 5 shows an electrolyzer test bed at the National Renewable Energy Laboratory. It consists of a 225-kW PEM electrolyzer stack from Giner Inc. with 29 cells. The DC operating voltage ranges from 40 V to 60 V. The higher heating value efficiency is approximately 83%. The response time for the full-range operation is in sub-seconds. Using full capacity, the stack produces approximately 4 kg of hydrogen. Hydrogen purity is critical to fuel cell applications. Impurities can cause significant

$Ramp_{rate} = 10/100$; assuming 10% ramp rate
for each time-step, t **do**
  Measure P_{PV_t}
  Recall $P_{EL_{t-\delta t}}$
  $\delta PV = P_{PV_t} - P_{PV_{t-\delta t}}$
  $P_{EL_t} = P_{EL_{t-\delta t}} + \delta PV$
  if $P_{EL_t} > Ramp_{rate} \cdot \frac{P_{PVrated}}{60sec} . \delta t + \delta P_{PV} + P_{EL_{t-\delta t}}$ **then**
    $P_{EL_t} = Ramp_{rate} \cdot \frac{P_{PVrated}}{60sec} . \delta t + \delta P_{PV} + P_{EL_{t-\delta t}}$
  end if
  if $P_{EL_t} < -Ramp_{rate} \cdot \frac{P_{PVrated}}{60sec} . \delta t + \delta P_{PV} + P_{EL_{t-\delta t}}$ **then**
    $P_{EL_t} = -Ramp_{rate} \cdot \frac{P_{PVrated}}{60sec} . \delta t + \delta P_{PV} + P_{EL_{t-\delta t}}$
  end if
  if $P_{EL} < P_{EL_{\min}}$ **then**
    $P_{EL} = P_{EL_{\min}}$: minimum operating limit
  end if
  if $P_{EL} > P_{EL_{\max}}$ **then**
    $P_{EL} = P_{EL_{\max}}$: maximum operating limit
  end if
end for

Algorithm 2. Ramp-Based Voltage Support.

Fig. 5. The 225-kW Giner stack at the National Renewable Energy Laboratory.

for each time step, t **do**
  if $f_{sys} > f_{nom}$ **then**
    $f(m_{droop}, f_{sys}, f_{nom}) = P_{f_{ref}} + m_{droop} \cdot \left(f_{sys} - \left(f_{ref} \pm DB\right)\right)$
    $P_{EL} = f(m_{droop}, f_{sys}, f_{nom})$
    if $P_{EL} < P_{EL_{\min}}$ **then**
      $P_{EL} = P_{EL_{\min}}$: minimum operating limit
    end if
    if $P_{EL} > P_{EL_{\max}}$ **then**
      $P_{EL} = P_{EL_{\max}}$: maximum operating limit
    end if
  end if
end for

Algorithm 1. Droop-Based Frequency Support.

degradation.

4.2. Power-Hardware-in-the-Loop test system

This section presents power systems used to demonstrate the value of integrating electrolyzers for frequency/voltage support.

4.2.1. Bulk system (frequency support)

To test the benefit of using electrolyzers for frequency support, a modified version of the two-area power system model [42] is used (Fig. 6). The net load on the system is 2.82 GW, with a peak load of 4 GW. As per PJMs regulation reserve guidelines [43], 1% of the peak load (40 MW) is maintained as regulation reserves using electrolyzers on the system and the Type 2 droop-based controller in Subsection 3.2. Two electrolyzers of 5-MW capacity are connected to each of the four buses (a total of 40 MW). Each electrolyzer operates at 50% (2.5 MW) of its rated capacity as the default. This allows for maximum available power in both directions, maximizing the benefit of the electrolyzers for grid support.

4.2.2. Distribution system (voltage support)

To test the voltage support for the distribution feeders, a simplified 8-bus model of a utility feeder is used (Fig: 7). The system has a net load of 10 MW, with 50% PV penetration (5 MW), and an equal amount of electrolyzer capacity (5 MW). Again, the electrolyzers are assumed to operate at 50% baseload to allow them the maximum ability to adjust to both positive and negative swings in the PV output. The sensitivity of the voltage support to the location of electrolyzers is not in the scope of this paper. In [44], we discussed the sensitivity of the electrolyzer locations to the improvement in system voltage.

4.3. Power-Hardware-in-the-Loop analysis

The PHIL study test cases account for disturbances in frequency and intermittency in PV output. They demonstrate the impact of controlled electrolyzer dispatch. Assumptions, PV profile days, and use cases are described next.

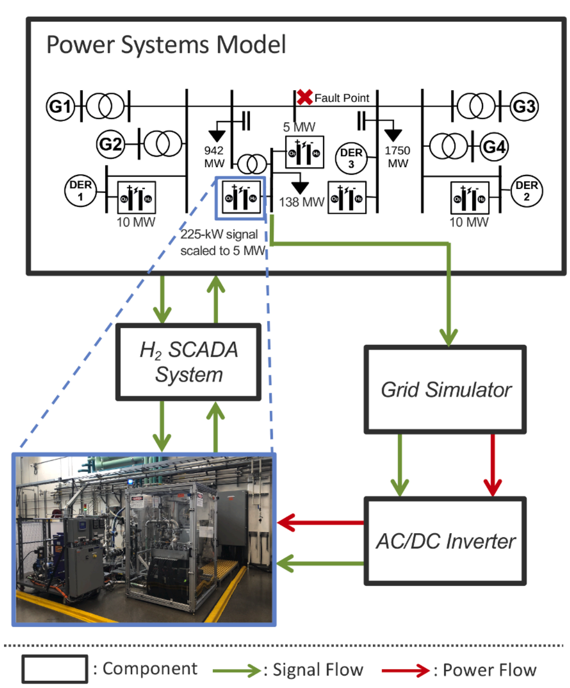

Fig. 6. Modified two-area power system model with DER penetration [42].

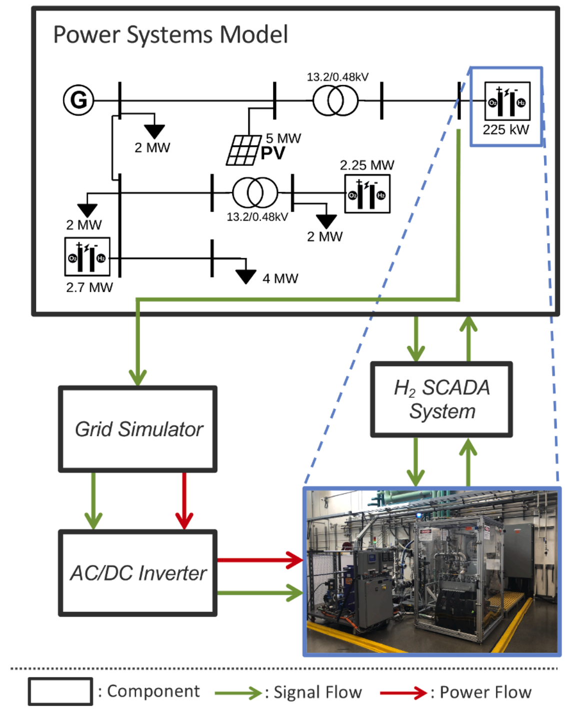

Fig. 7. Simplified 8-bus distribution feeder model.

4.3.1. Frequency support use cases

For bulk systems, faults and other events cause an imbalance between load and generation (Section 4.2.1). This is a primary cause of frequency disturbances. The following use cases analyze the frequency response with and without electrolyzer support. Multiple frequency disturbances are present for 0%, 25%, and 50% DER penetration levels.

1. Case 1A: Loss of 1% load— A positive trend frequency oscillation is induced by simulating a loss of 1% system load. The response of the electrolyzers and the resulting frequency response with and without electrolyzer control will be compared.
2. Case 1B: Gain of 1% load— A negative trend frequency oscillation is induced by simulating a gain in 1% of the system load. The response of the electrolyzers and the resulting frequency response with and without electrolyzer control will be compared.
3. Case 1C: Temporary three-phase fault— A temporary three-phase fault causes a sharp increase in current demand and a consecutive voltage decline. This case captures the resulting frequency response in the system with and without electrolyzer-based frequency support.

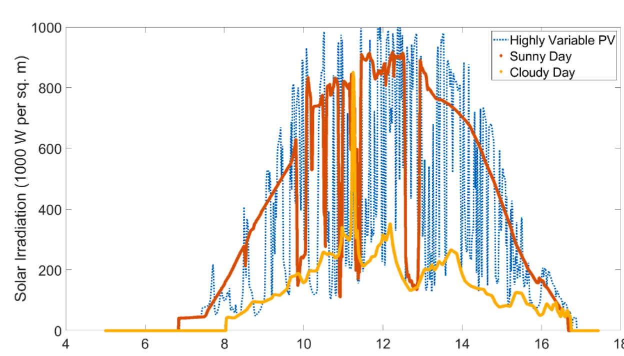

Fig. 8. PV profiles for a) highly variable, b) sunny, and c) cloudy day.

4.3.2. *Voltage support use cases*

During normal operations in a distribution system, intermittent DER output is among the primary contributors to change system voltage (Section 4.2.2). Three representative days (Fig. 8) are chosen to represent and analyze the participation of electrolyzers for voltage support.

- *Case 2A: Sunny day*—Representative day with high PV output, low variability
- *Case 2B: Cloudy day*—Representative day with low PV output, medium variability
- *Case 2C:Highly variable day*—Representative day with variable PV output, high variability.

5. Results and analysis

This section presents the results for the outlined case studies in real-time HIL using RTDS tests (Sections 4.3.1 and 4.3.2). The PHIL setup using EMT models in RTDS validated that signals can be accurately followed in real time by a physical electrolyzer.

5.1. *PHIL: Frequency response for bulk grid system*

These use cases (outlined in Section 4.3.1) demonstrate the improvement in the frequency response of the bulk power system with electrolyzers' participation. The individual frequency disturbances are discussed now.

5.1.1. *Case 2A: Change in system load (loss of load)*

A sudden change in system load can induce severe frequency oscillations spanning several seconds (or minutes). This is further exacerbated by reduced inertia for systems with high DER penetration levels. Loss-of-load events have tighter bounds to prevent a generator trip. In response, the droop can temporarily increase the electrolyzers' load to help balance the system's net load.

The results presented here show the changes in system frequency given the loss of 40 MW of load for the 0%, 25%, and 50% DER penetration cases. Consecutively, the electrolyzers helped reduce the swings by up to 59 mHz (Fig. 9) and increased frequency damping. Fig. 10 shows that the generators in the system oscillate at different speeds given the area. As a result, the normalized response of the electrolyzers in the same area will be largely similar but might vary drastically between areas (Fig. 11). Overall, the extent of change in generator speeds is less with electrolyzer-based frequency response.

5.1.2. *Case 2B: Change in system load (load gain)*

Similar to load loss, a sudden load gain will cause a frequency decline. The droop response of electrolyzers can temporarily reduce system load and limit unbalance.

The results presented here show changes in system frequency given a gain of a 40-MW load. The electrolyzers help reduce swings by up to

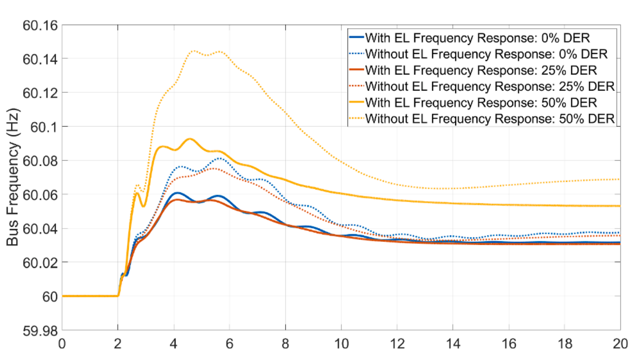

Fig. 9. Frequency: load loss with 0%, 25%, 50% DERs.

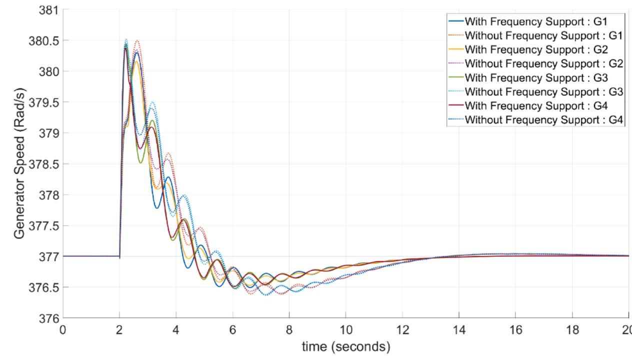

Fig. 10. Comparison: speeds of machines G1–G4 for load-loss event.

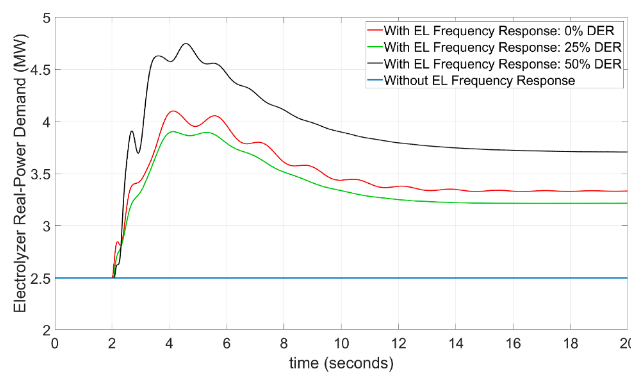

Fig. 11. Electrolyzer response: load-Loss with 0%, 25%, 50% DERs.

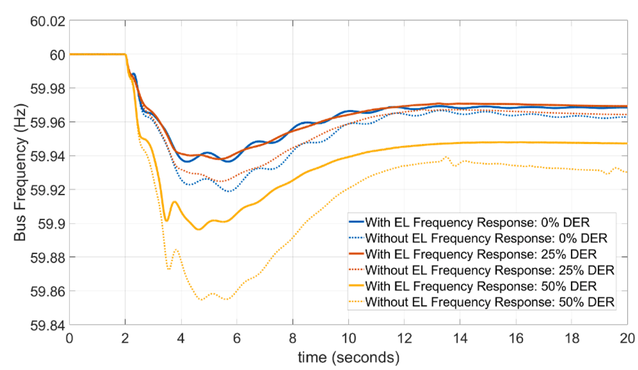

Fig. 12. Frequency: load gain with 0%, 25%, 50% DERs.

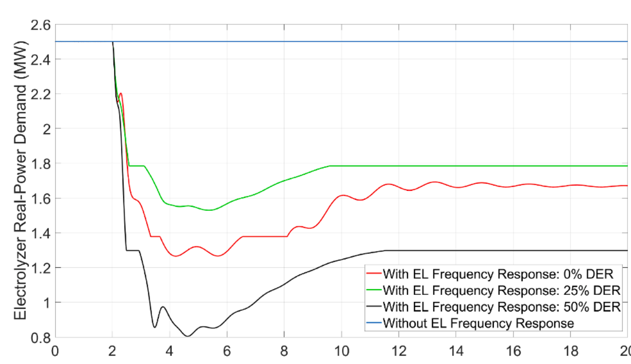

Fig. 13. Electrolyzer response: load gain with 0%, 25%, 50% DERs.

46.34 mHz (Fig. 12) with increasing DER penetration level and offer better frequency damping. Similar to Case 2A, electrolyzers respond differently to the given event based on local frequencies (Fig. 13).

5.1.3. Case 2C: Fault-Induced disturbance

When a fault strikes, the sudden increase in current and consecutive voltage drop can induce a frequency excursion in the system. In this case, a temporary (six-cycle) three-phase fault was induced at Point ‘A’ on System 2 (Fig. 6). In this case, the system frequency increases (Fig. 14), thereby resulting in a load loss on the electrolyzers (Fig. 15). For this event, a reduction in frequency deviation of up to 75 mHz was observed for 50% DER penetration levels.

5.1.4. Summary

Table 1 summarizes the largest improvements in overall frequency deviation with increasing DER penetration levels for different frequency events. With only 1% of the peak system load (40 MW) as electrolyzers, an improvement of up to 75 mHz in maximum frequency deviation is shown. Active participation from the electrolyzers also improves the frequency damping (Table 2). In all the cases, it takes many more seconds for the frequency to settle within 5% of its steady-state value after a disturbance. Using a 4% criterion, the post-disturbance frequencies do not settle within the 20-second window without electrolyzer participation.

5.2. PHIL: Voltage response for distribution grid system

These use cases demonstrate the improvement in system voltage along with distribution system feeders with electrolyzers’ participation (Section 4.3.2). The distribution system (Fig. 7) is used to analyze the system voltage profile with and without electrolyzers for voltage support.

5.2.1. Results: Generation vs. demand—With and without electrolyzer control

These results demonstrate that a controlled electrolyzer load can change quickly to absorb power ramps caused by changing PV output. Here, high PV penetration cases are shown for cloudy, highly variable, and sunny days (Fig. 8). Figs. 16 and 17 present comprehensive load vs demand profiles for highly variable PV days with and without electrolyzer participation for voltage support to demonstrate this observation. As shown, the net demand from the substation does not change as aggressively.

Top voltage plot in Fig. 18 compares the voltages with and without electrolyzer support (Figs. 16 and 17 respectively) shows the voltage improvement. With electrolyzer support (voltage in green) is smoother compared to the base scenario (voltage in red) - when the electrolyzer load is not modulated to support the grid.

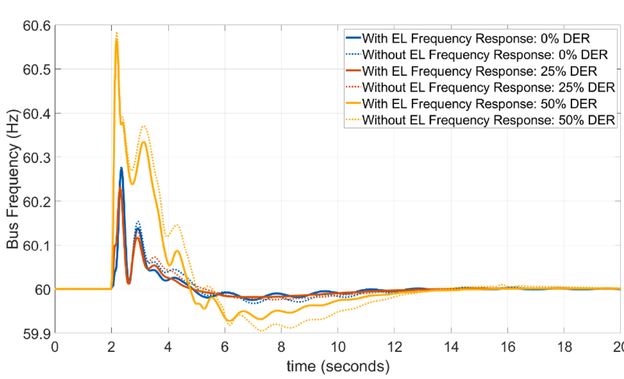

Fig. 14. Frequency: temporary fault with 0%, 25%, 50% DERs.

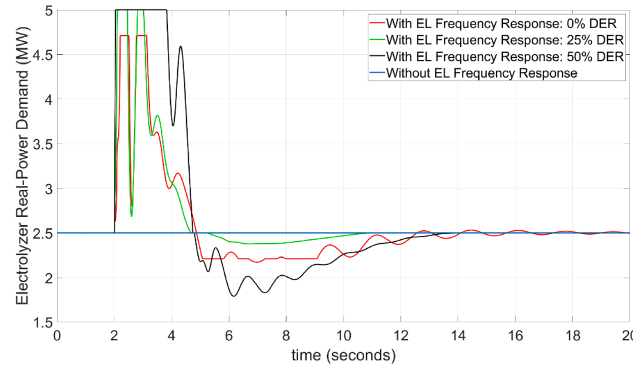

Fig. 15. Electrolyzer response: temporary fault with 0%, 25%, 50% DERs.

Table 1
Summary: Maximum Reduction in Frequency Deviations.

Event → DER Penetration ↓	Loss of Load (mHz)	Gain of Load (mHz)	Temporary Fault (mHz)
0	22.31	17.8	20.87
25	30.17	23.39	26.5
50	58.88	46.34	74.96

Table 2
Summary: Frequency Settling Time (5% of Steady-State Value).

Event → DER Penetration ↓	Loss of Load (sec)	Gain of Load (sec)	Line Fault (sec)	Electrolyzer Participation
0	13.102	17.655	11.135	No
	11.051	11.095	10.759	Yes
25	14.391	18.036	11.831	No
	11.092	11.325	11.018	Yes
50	18.198	$>$20	12.923	No
	11.327	12.202	11.912	Yes

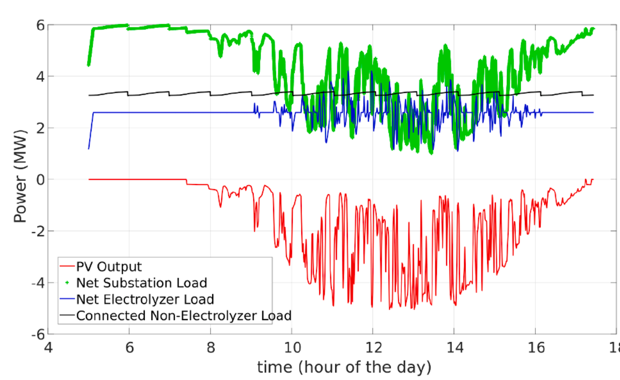

Fig. 16. Net generation vs. demand for highly variable PV day: with electrolyzer control.

5.2.2. Results: Tap operations: With and without electrolyzer control

Electrolyzer support reduces power exchange at the substation and improves distribution system voltage. This improves system voltage and reduces LTC operations. Fig. 18 presents the voltage profile at one of the system buses (B3) given the change in PV output for highly variable PV day. Fig. 19 shows the voltage profile at bus B4 for a cloudy day. Similarly, Fig. 20 shows the voltage profile at bus B5 for a mostly sunny day. As shown, depending on the location of buses, voltage profiles can still see improvements during short periods of changes in DER output

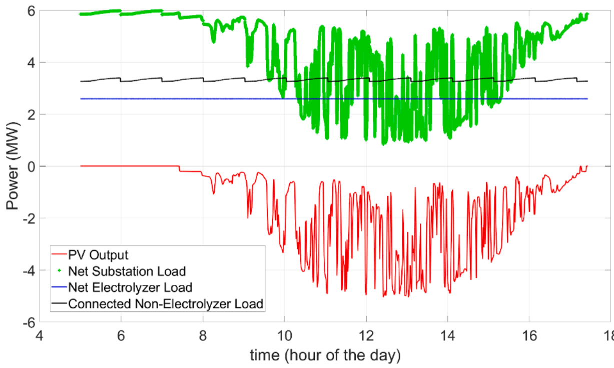

Fig. 17. Net generation vs. demand for highly variable PV day: without electrolyzer control.

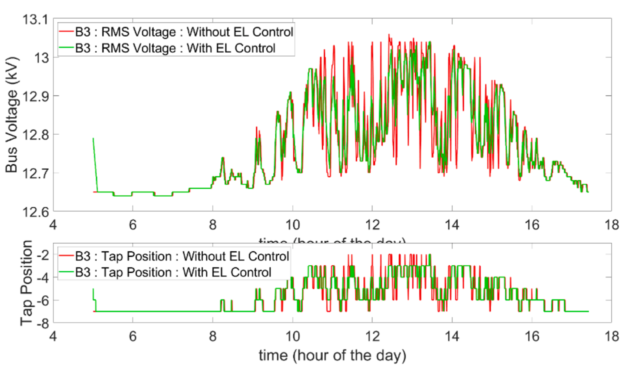

Fig. 18. Bus B3: voltage, tap operations on highly variable PV day.

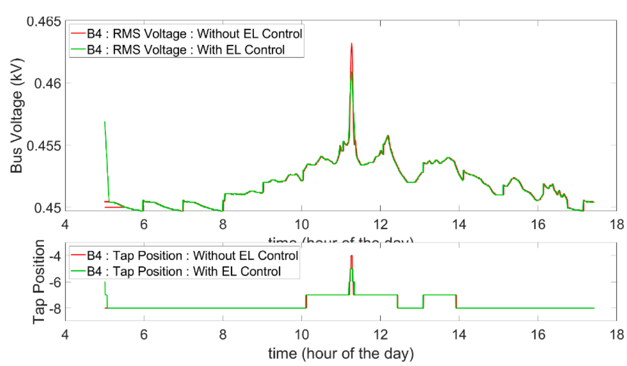

Fig. 19. Bus B4: voltage, tap operations on cloudy day.

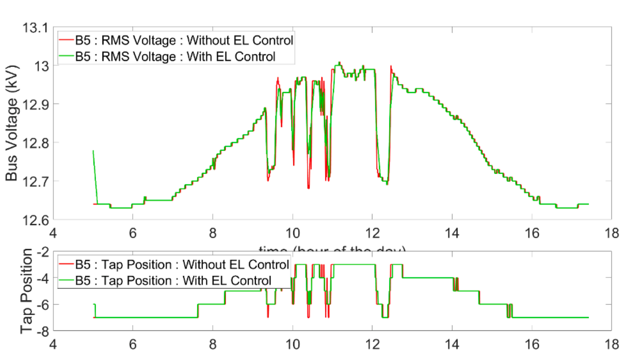

Fig. 20. Bus B5: voltage, tap operations on sunny day.

Table 3
Summary: Reduction in Tap Operations with Electrolyzer Control.

Bus	Profile	Reduction in Tap Changes
Substation	Cloudy day	4 (15.38%)
	Day with highly variable PV	90 (30.61%)
	Sunny day	10 (17.86%)
B3	Cloudy day	2 (5.88%)
	Day with highly variable PV	94 (29.01%)
	Sunny day	8 (7.55%)
B4	Cloudy day	10 (26.32%)
	Day with highly variable PV	112 (26.42%)
	Sunny day	54 (27.55%)
B5	Cloudy day	2 (2.08%)
	Day with highly variable PV	84 (26.42%)
	Sunny day	62 (34.83%)

(PV, in this case). In all cases, there is some reduction in the number of LTC operations, thereby improving their overall life and reducing operational downtime (Table 3, Figs. 18, 19, 20).

5.2.3. Summary

Table 3 summarizes potential reduction in operations of LTCs with electrolyzer participation. As expected, the most significant reduction in LTC operations was observed for a highly variable PV day. Tap operations with electrolyzer support are reduced by up to 35% [44].

5.3. PHIL: Hydrogen production

This subsection analyzes H_2 production for the case of a highly variable PV day in response to mitigating voltage disturbances. Electrolyzers consume electric power to produce hydrogen electrochemically. The empirical equation from the electrolyzer stack used for HIL analysis is given:

$$\dot{m}_{H_2} = 0.01674.P_{EL} + 0.0160 \quad (8)$$

where $\dot{m}_{H_2}$ is the mass flow rate of hydrogen production (kg/h), and P_{EL} is net electrolyzer power consumption (kW). The empirical equation for hydrogen production rate is based on the Faraday's Law of electrolysis that shows that the current drawn is proportional to the mass flow rate of hydrogen. This equation was obtained by using polynomial fit on data logs of multiple 225-kW electrolyzer stack runs. The trend was largely linear, thereby resulting in Fig. 21.

Figs. 21, 22 show the relationship between electrolyzer power consumption and cumulative hydrogen production for highly variable PV day. Although the scenario without electrolyzer control illustrates steady power consumption throughout the simulation period, controlling electrolyzers introduces variable-power draws to mitigate voltage disturbances, as discussed in Section 5.2. Because of rapid and

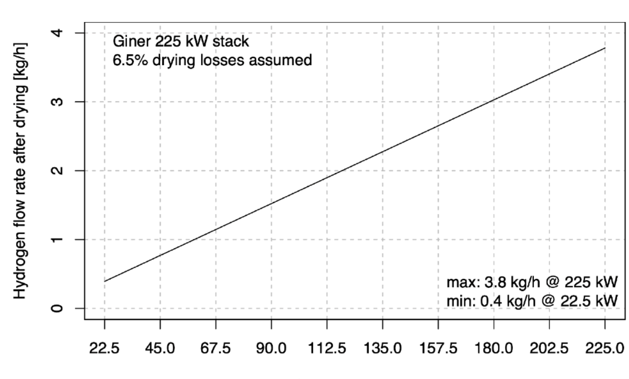

Fig. 21. Hydrogen production rate: 225-kW Giner stack.

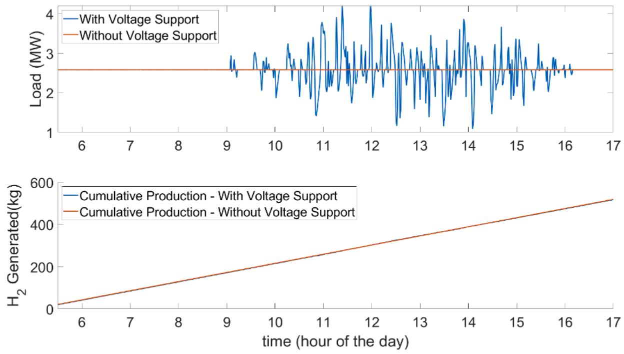

Fig. 22. Electrolyzer power consumption and cumulative hydrogen production for highly variable PV day.

instantaneous changes in electrolyzer demand, the impact on H_2 production at a given time is minimal. In other words, cumulative H_2 production is relatively steady (Fig. 22). Both scenarios estimated approximately 540 kg of hydrogen production throughout the simulation period, which approximately fills 100 FCEVs after compressing and dispensing hydrogen [45]. For all three test profiles, the difference in hydrogen production with and without electrolyzer control was within 0.3%. These results confirm that controlling electrolyzers not only mitigates voltage disturbances but also produces high-value fuel without significantly affecting the amount of hydrogen produced compared to scenarios without electrolyzer control.

In the present context, it might be impractical to operate a high-capital-cost electrolyzer at only 50% of rated capacity without a reasonable incentive. However, this paper validates ancillary services as a potential revenue stream using electrolyzers instead of traditional energy storage systems. To optimize the economic viability of this stream, future work will consider optimizing hydrogen generation based on both time-of-use electricity rates and hydrogen economy demands. The objective will be to meet production goals at minimal cost and support the grid during peak demand hours. Further, because hydrogen refueling stations typically install multiple hydrogen storage tanks with different pressure levels, this modification would help size the fueling station, control the production rate, and schedule hydrogen compression for FCEV demands.

6. Discussion: Implementation challenges and opportunities

An important question when considering unconventional use cases for P2G systems is how H_2 production and system response will be impacted under the new operating paradigm. This section summarizes challenges and opportunities with technical implementation given the use cases considered for this paper.

6.1. Communication and response delays

As demonstrated in Section 5, frequency and voltage support have different control requirements. Section 2.1 demonstrates that providing frequency support needs the respective system to be highly controllable with fast reaction time. Electrolyzers have already demonstrated their suitability (response time $<$200 ms) for these applications [16]. Similar to other operating reserves, communications delays between controller dispatch and electrolyzer response can further limit the impact on system frequency and must be carefully considered. For the laboratory PHIL setup, the round-trip communication delay was approximately 100 ms (Fig. 23). In other words, an onboard primary control embedded into the electrolyzer front-end controller might be ideally placed to reduce the communication delay and be more beneficial for frequency support applications. However, this might limit opportunities for coordinated control across regions and system-level optimization.

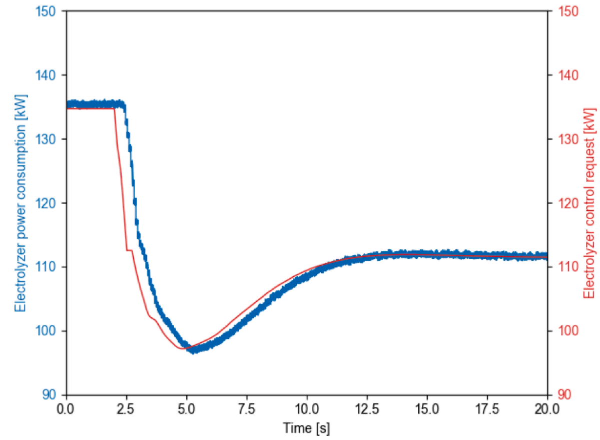

Fig. 23. Cumulative Delay Between Power Dispatch Signal and Electrolyzer Response.

System impedance and reactive power exchange limit the impact of any event on the voltage across the system. Therefore, voltage support is not as time-sensitive. In other words, distribution systems can use slower electrolyzers and/or controls to optimize cost vs benefit. This also provides opportunities for coordinated control that would not be possible for frequency support applications.

6.2. Converter efficiency

Round-trip efficiency is crucial for both long-term storage and real-time system support. We used Magna-Power MT Series converters for these experiments. Four Magna-Power converters were connected in series to provide a maximum of 4000A DC and 250V DC output to electrolyzer stack. The controller in the model sends current set-points to operate the converters. The converter used for PHIL set up in this paper has an efficiency (Fig. 24) of approximately 80%—primarily because of operating in lower limits of its operating range. Because the objective of grid support is to modulate electrolyzer load between its minimum and maximum limits, related converter operating limits and efficiency should be carefully evaluated. Concerning Fig. 21, larger efficiency losses might have a cumulative impact on hydrogen production and/or grid support. In other words, dispatch can also impact cost-benefit studies and might need to be rescaled.

6.3. Balance of plant for the electrolyzer

In addition to converter efficiency, the balance of the plant for the electrolyzer also dictates hydrogen production. Given the operating temperature and output power, among other factors, there will be a

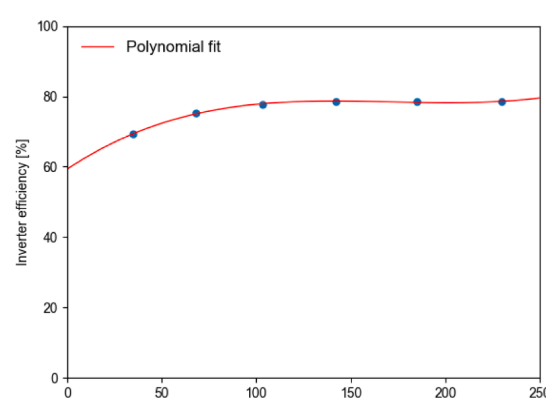

Fig. 24. Inverter Efficiency Curve as a function of Output Power.

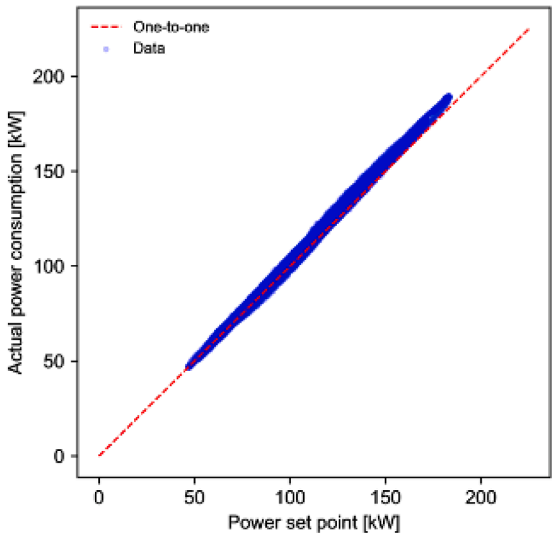

Fig. 25. Linear distribution: actual power consumption vs signal.

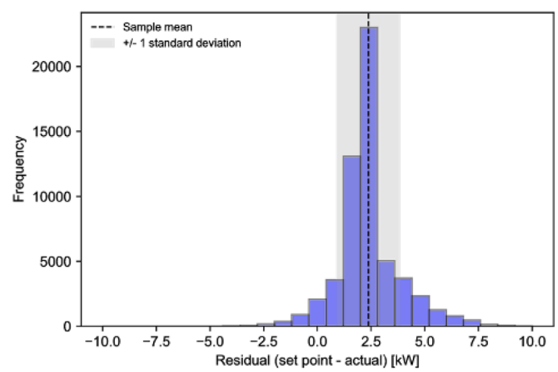

Fig. 26. Residual distribution of mean deviation: actual power consumption vs signal.

deviation in the H_2 output. Figs. 25, 26 compare the difference between requested and actual power consumption by the electrolyzer stack. During the PHIL test, we observed a 1% offset between the dispatch command and the resulting power consumed by the electrolyzer. Depending on the scale of the application and apparatus used, the offset could vary. The electrolyzer efficiency and operating conditions must be carefully considered because they can result in a cumulative difference between intended vs actual H_2 produced and/or electrolyzer operating conditions.

7. Conclusions

This paper evaluated using electrolyzer-based P2G systems for frequency (bulk grid) and voltage (distribution) support in the electric grid. The literature demonstrates that P2G systems have a significant competitive advantage over BESS in the long run. P2G systems can positively contribute to the reliability of the electric grids from a wide-area and planning perspective. Therefore, this paper formulates and demonstrates the implementation of P2G-based grid support using real-time PHIL tests with a 225-kW PEM electrolyzer stack. The electrolyzers in the electric grid are modeled as controllable loads, and corresponding frequency and voltage controller designs are presented. Improvement in system frequency (bulk grid) and voltage (distribution grid) with electrolyzer support are analyzed for 0%, 25%, and 50% DER penetration levels. Results show that electrolyzer controls satisfy performance requirements for both fast (frequency) and slow (voltage) response requirements and show substantial improvements in grid operating conditions. An improvement of up to 75 mHz in frequency with much faster damping for the bulk grid is observed, whereas voltage support resulted in a reduction of up to 112 LTC operations on the distribution grid. The hydrogen generation estimate from electrolyzer dispatch also validates that the impact on daily hydrogen generation is negligible. Finally, the paper discussed the nuances of physical hardware setup - i) the impact of communications delays, ii) the need to model the inverter efficiency, and iii) deviations from the control signals and measured values. These factors can have a significant impact on the performance of P2G systems for grid support and need to be considered carefully.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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