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Transforming ENERGY

Validation of interconnection and interoperability of grid-forming inverters sourced by Hydrogen technologies in view of 100% renewable microgrids

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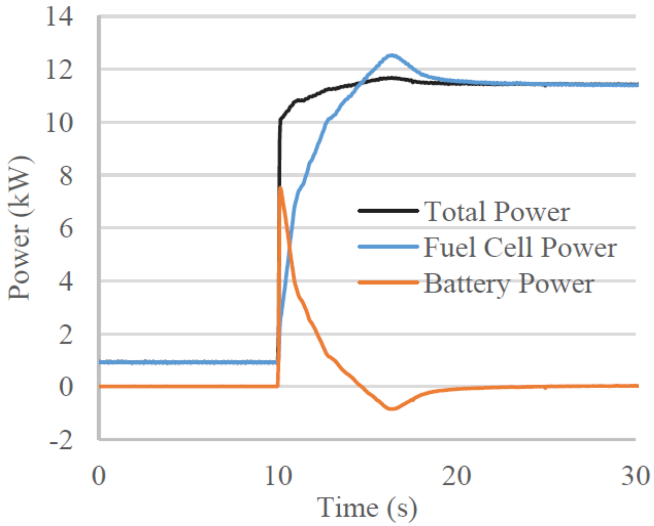
Project ID: TA062

Project Goal

Grid-forming inverters are becoming key assets in distribution systems with microgrids. Fuel cell-coupled grid-forming inverters have the potential to successfully act as grid-forming assets.

Project goals

- Develop a test bed to evaluate and document updates to interconnection and interoperability requirements for grid-forming fuel cell inverters.
- Leverage existing Advanced Research on Integrated Energy Systems (ARIES) assets to run hardware-in-the-loop experiments.
- Interconnection and interoperability updates identified through this project will provide cost improvements for the utilities in the United States and increase the value of grid-forming fuel cell inverters.
- Accelerate industry adoption of grid-forming fuel cell inverters as a key component in distribution systems/microgrids.



Experimental results from a proton exchange membrane fuel cell (PEMFC)/battery hybrid system responding to a step increase in electrical demand from 0 kW to 9 kW at 10 seconds [1]

[1] L. Zhao *et al.*, "Dynamic Performance of an In-Rack Proton Exchange Membrane Fuel Cell Battery System to Power Servers," *Int. J. Hydrogen Energy*, 42, no. 15 (2017), pp. 10158–10174.

Overview

Timeline and Budget

- Project start date: 01/01/22
- Project end date: 12/31/24
- Total project budget: $1,689,000
  - Total DOE share: $1,189,000
  - Total cost share: $500,000
  - Total DOE funds spent*: $400,000
  - Total cost share funds spent*: $156,221
    - * As of 03/07/2024.

Barriers

- Barriers and targets:
  - Lack of standardized interoperability and interconnection requirements for grid-forming fuel cell inverters
  - Intelligent electronics device capability description (ICD) file development and hosting in the public domain
  - First-of-its kind power hardware-in-the-loop (PHIL) setup to run grid-forming inverter experiments
  - Complete PHIL and controller hardware-in-the-loop (CHIL) integration with microgrid model.
  - Complete test plan execution in hardware setup.

Partners

- NREL
- Sothern California Gas Company
- University of California, Irvine (UCI).

Relevance/Potential Impact

- The efforts taken in this project aim to standardize the sensing (interoperability), operation (interconnection), and control (through the microgrid controller) of grid-forming fuel cell inverters.
- Successful updates to the standards *will reduce the cost of the installation, operation, and control of grid-forming fuel cell inverters* and enable them to functionally replace traditional generation, resulting in greater market potential and installation at scale.
- The outcomes of this work directly aim to reduce the costs of the integration of hydrogen assets into the grid, specifically, interoperability and interconnection costs. The outcomes are available in open source for U.S. manufacturers to use and reduce their smart grid integration costs.

Approach

The goal of the project is not to create new standards or requirements but to propose updates to existing standards.

- IEEE 1547-2018 – IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
- UL 1741 Supplement SA: Grid Support Utility Interactive Inverters and Converters (Underwriters Laboratories, 2016)
- CSA C22.3 No. 9: Interconnection of Distributed Energy Resources and Electricity Supply Systems (Draft) (Mississauga: Canadian Standards Association (CSA), 2019)
- California Rule 21, Hawaii 14H
- Few national grid codes in the European Union.
- IEC 61850 – Communication Networks and Systems for Power Utility Automation – Part 7-420: Basic Communication Structure – Distributed Energy Resources and Distribution Automation Logical Nodes
- DNP3 Application Note AN2018-001 – DNP3 Profile for Communications with Distributed Energy Resources
- P2030 Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads.

Budget Period 1

- Complete shakedown experiments
- Reserve ARIES equipment
- Complete initial draft of DRTS model
- Complete experiments with fuel cell inverter

Budget Period 2

- Interoperability programming in XML or JSON format
- Complete recommendation documentation of interoperability and interconnection
- Complete integration of CHIL with DRTS model
- Integration of PHIL with the DRTS microgrid model, DEI report

Budget Period 3

- Complete test case documentation
- Complete three test cases
- Disseminate results in final IAB meeting
- Complete interconnection and interoperability report

Power Hardware

Grid-forming inverter power hardware experiments and PHIL experiments

(a) Fuel cell inverter

(b) Fuel cell stack setup

Fuel cell inverter and fuel cell stack setup leveraged from ARIES lab setup. ***Photos by NREL***

- Run PHIL experiments with grid-forming fuel cell (100-kW) inverter and enable transition between grid-following and grid-forming modes of operation.
- Identify necessary updates to interconnection standards.

Controller Hardware Setup

DRTS to support both PHIL and CHIL experiments

(a) RTDS Novacor rack	(b) Microgrid controller

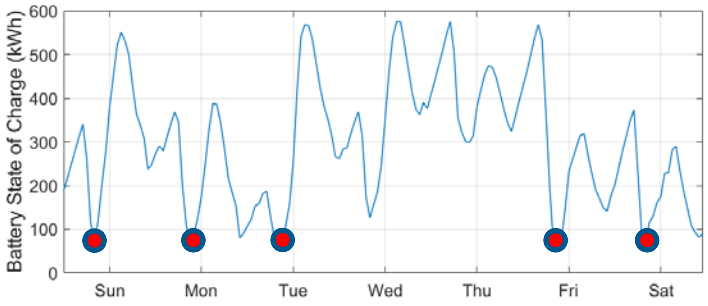
Controller hardware equipment. *Photos by NREL*

- Microgrid modeled in RTDS
- Microgrid controller with grid-following/grid-forming inverter mode change capability
- Identify updates to interconnection standards for microgrid operation and gid-forming capability.

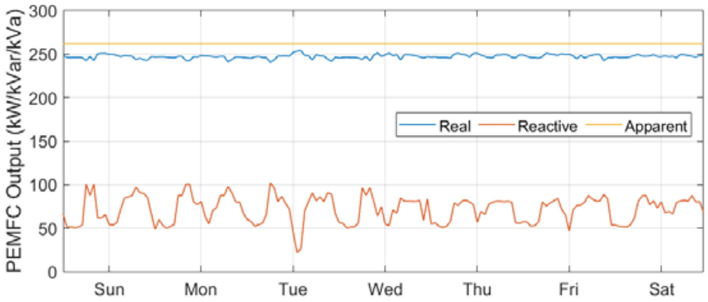
Accomplishments and Progress

- Solar + storage only
  - 3.6 MW solar PV, 1.2 MWh battery storage
  - Cost: $0.77/kWh electricity

- Solar, storage, and fuel Cells
  - 0.32 MW solar PV, 1.2 MWh battery storage, 260 kW PEMFC backup
  - No SOFC
  - Cost: $0.22/kWh electricity



Aggregated battery state of charge during a resiliency event. Red dots indicate where minimum state of charge occurs and firm backup generation is needed to ensure stable microgrid operation

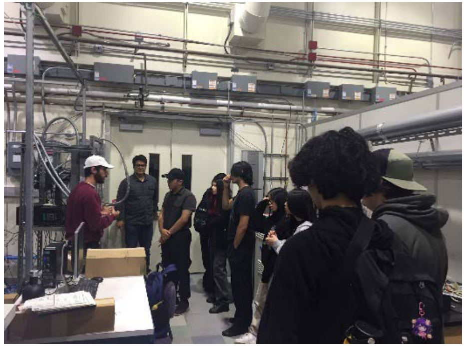


PEMFC power output during a resiliency event showing baseload operation with dynamic real/reactive power production

Accomplishments and Progress

- Completed high school and college visits
  - Led three tours of UCI H_2 research laboratories and campus
  - Conducted hands-on water splitting and electric motor experiments
  - Hosted student panels on “day in the life” of engineering undergrads






High school students visiting and touring UCI research laboratories and campus, Photos by Robert Flores

Accomplishments and Progress

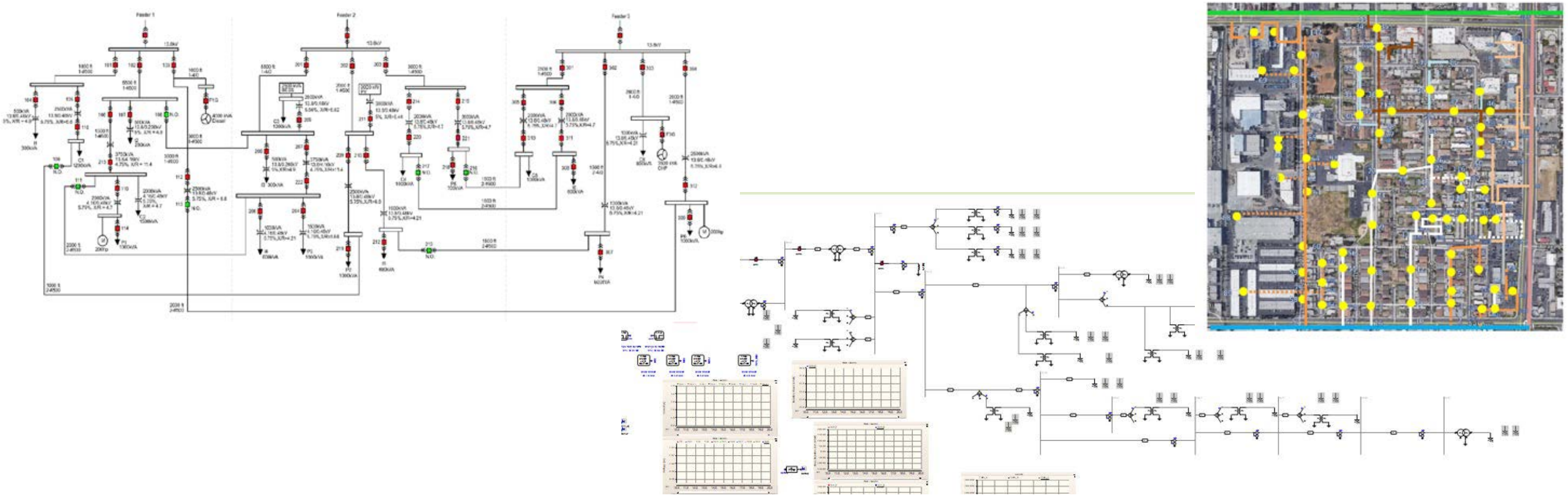
- Presented at the Oak View Science Club
  - Summer science club with K – 5^{th} grade students
  - Focused on hands-on experiments
  - Averaged 20 students per session
  - Received support from UCI engineering graduate students

Examples of different experiments and activities (clockwise from top left): (1) water splitting, (2) egg drop, (3) solar power, and (4) homemade electric motor, Photos by Robert Flores

Accomplishments and Progress

- Successfully completed PHIL experiments with grid-forming fuel cell inverter.
- Successfully published and presented paper in IEEE conference to disseminate the methodology to run PHIL experiments with grid-forming inverters.
- Procured multiple microgrid controllers to work with the Banshee microgrid model.
- Completed modeling of a few microgrid models to go beyond the test microgrid system.

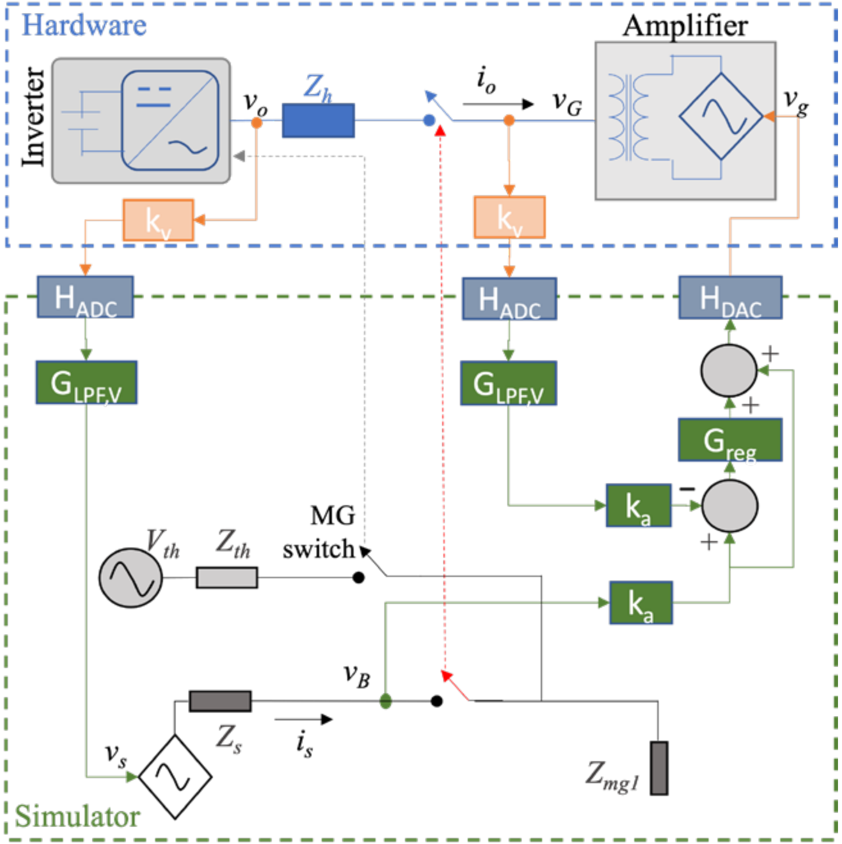
Accomplishments and Progress

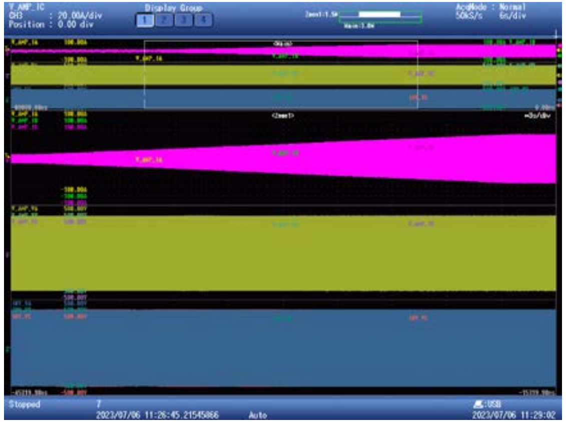


Completed and working on the following microgrid models:

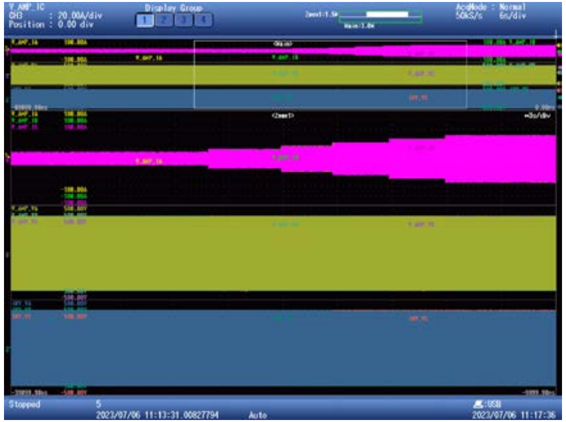
- Banshee microgrid model, imaginary microgrid model.
- Oak View Community, Huntington Beach, California – disadvantaged community with aging electrical infrastructure and a critical city water pumping station.
- Real microgrid in North Carolina under North Carolina Electric Membership Corporation and Wake Electric Cooperative.
- Igiugig, Alaska – isolated microgrid power system.

Accomplishments and Progress





Scope capture of the inverter dispatch change in grid-connected operation showing the (top) current, (middle) the amplifier voltage, and (bottom) inverter voltage.



Scope capture of the load step change in islanded operation showing the (top) current, (middle) the amplifier voltage, and (bottom) inverter voltage.

Response to Previous Year's Reviewers

Primarily positive feedback. Selected comments and responses below

Reviewer comments	Response
The project takes a logical approach. The team could leverage work done by fuel cell companies—such as Bloom Energy, FuelCell Energy, and Doosan NA—that have stationary fuel cell systems installed and have dealt with grid connection and interoperability issues.	We are working with Bosch to understand the fuel cell company perspective and disseminate results to the fuel cell manufacturer community. We are also working with grid operators from North Carolina and multiple vendors that provide controllers to grid operators (ETAP, OATI, PXiSE, S&C, Siemens).
It would be beneficial to have more collaboration with a grid operator, perhaps having a grid operator on the advisory board. Additional collaboration with fuel cell manufacturers/providers would be beneficial (Bloom Energy, Ballard Power Systems, Doosan NA, FuelCell Energy, Cummins, Inc., Plug Power Inc., etc.). Some of these have microgrid systems and systems that operate on the grid already.	
Collaboration with fuel cell companies is limited.	

Response to Previous Year's Reviewers

Primarily positive feedback. Selected comments and responses below

Reviewer comments	Response
This project is about halfway through its intended duration, but costs incurred to date are less than 10%. It is unclear if this is in line with the expected budget.	Most costs will be incurred during the test plan execution stage. We were able to share the cost of purchasing the microgrid controller equipment with other projects. This has resulted in some cost savings in the project.
DC coupling storage behind the GFM inverter would be valuable. The current PHIL allows for testing of alternating current (AC)-coupled storage, which is definitely valuable. The inclusion of DC-coupled storage may change some of the control paradigms around the fuel cell.	We plan to use fuel cells in some experiments and controllable DC supply in some experiments. We are able to program the ramp rates of fuel cell plus battery in our controllable DC supply scenarios.

Collaboration and Coordination

Partner	Role
Southern California Gas Company	Cost share partner, DEI contributor.
University of California, Irvine	DEI task lead. analysis lead.
Etap	Microgrid controller vendor.
Triangle Microworks	Interoperability code commercialization partner.

Industry advisory board	Topic of interest
NIST	Interoperability/interconnection.
Bosch	Fuel cells supporting grid-forming operation
Washington State University	Fuel cell inverter operation in distribution system
Schatz Energy Research Center	Interoperability/interconnection

Industry advisory board meetings are held at least twice per year to update on progress and receive feedback.

Remaining Challenges and Barriers

- Test plan execution – time limitations on PHIL setup due to safety and security constraints.
- Requires more in-depth review processes to complete recommendations to standards.

Proposed Future Work

- Interoperability
  - Complete standards recommendations documentation and submit the document for review and dissemination in open source.
- Interconnection
  - Execute the test plan using the integrated experimental setup (2024).

Summary

- Developed ICD files to enable interoperability to electrolyzers and fuel cells.
- Demonstrated the developed codes in BeagleBone Board. This reduces the cost of enabling communications to hydrogen assets and integrating them into the distribution system.
- Integrated microgrid controller with digital real time simulation model of Banshee microgrid model.
- Completed PHIL interface for grid-forming fuel cell inverter operation.
- Completed a paper and presented the work at an IEEE conference.

Thank You

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Technical Backup and Additional Information

Technology Transfer Activities

- Open-source software record submitted - SWR-23-42.
- No additional technology transfer activities.

Special Recognitions and Awards

- PHIL interface was a part of the R&D 100 award titled “Simulation and Emulation for Advanced Systems (SEAS): Bridging the Gap Between Energy Transition Planning and Implementation”.

Publications and Presentations

- Pratt, A., K. Prabakar, S. Ganguly, and S. Tiwari. 2023. "Power-Hardware-in-the-Loop Interfaces for Inverter-Based Microgrid Experiments Including Transitions." Presented at the 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, 537–544.
- Chaired and presented work on a panel session at the IEEE Innovative Smart Grid Technologies (ISGT) LA conference
- Presented a webinar on "Fuel Cell Modeling, Sizing, and Standards in Microgrids with ETAP Software."
- Presented a poster at a fuel cell seminar titled "Interconnection and Interoperability Requirements of Hydrogen Assets to Enable Grid Integration."
- Developing a journal article on the optimization of grid-forming fuel cells supporting microgrid operation.