Hardware-in-the-Loop Using Electromagnetic Transient Simulation

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Contents

Energy Systems Integration Facility

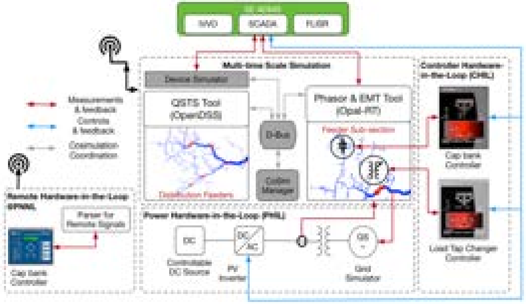
The Energy Systems Integration Facility (ESIF) is a national user facility located in Golden, Colorado, on the campus of the National Renewable Energy Laboratory (NREL).

http://www.nrel.gov/esif *Photo by NREL*

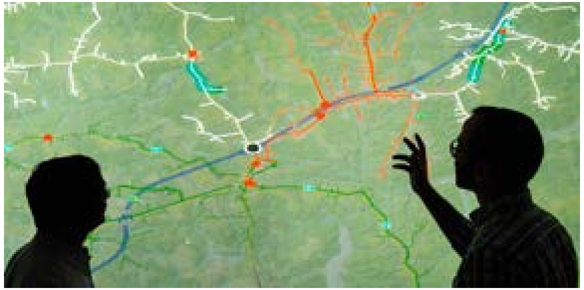
Controller- and Power-Hardware-in-the-Loop

NREL's megawatt-scale controller- and power-hardware-in-the-loop (CHIL/PHIL) capabilities allow researchers and manufacturers to test energy technologies at full power in real-time grid simulations to safely evaluate performance and reliability.

Microgrids



Cosimulation



Power system studies

Photos by NREL

Technology Readiness Levels (TRLs)

- Metric system developed to support the assessment of the maturity of a technology
- Allows for consistent comparisons of maturity among different types of technologies
- Used in the space industry
- Nine levels of maturity are identified in the original paper (Mankins 1995).
- At present, even high level TRLs need continuous evaluation post deployment.

Technology Readiness Level	
TRL 1	Very low cost, idea
TRL 2	Low cost, idea
TRL 3	Moderate cost, idea to proof
TRL 4	Moderate cost, proof of concept
TRL 5	Moderate cost, proof of concept
TRL 6	Increased cost, validation
TRL 7	Increased cost, validation
TRL 8	High cost, deployment
TRL 9	Ideally market price, production stage

Source: Mankins 1995

Technology Readiness Levels

Technology Readiness Level	
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 9	Actual system "flight proven" through successful mission operations

Source: Mankins 1995

Borrowing Technology Readiness Levels for Power Systems

- What is a proof of concept?
- What is a breadboard validation in a laboratory environment?
- What is a relevant environment?
- What is a demonstration?

Source: Mankins 1995

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- What is a relevant environment?
- What is a demonstration?

- Boundaries of physics
- Electromagnetic transient (EMT) simulation
- Dynamic simulation
- Steady-state simulation
- Hardware experiments
- Software experiments
- Hardware-in-the-loop experiments
- Field deployment.

Source: Mankins 1995

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- Boundaries of physics
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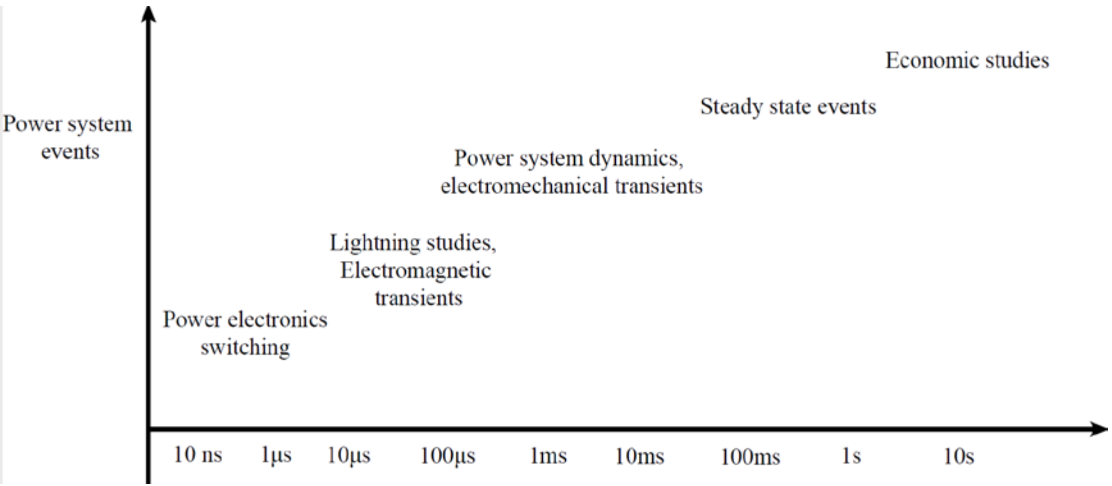
- Field deployment.

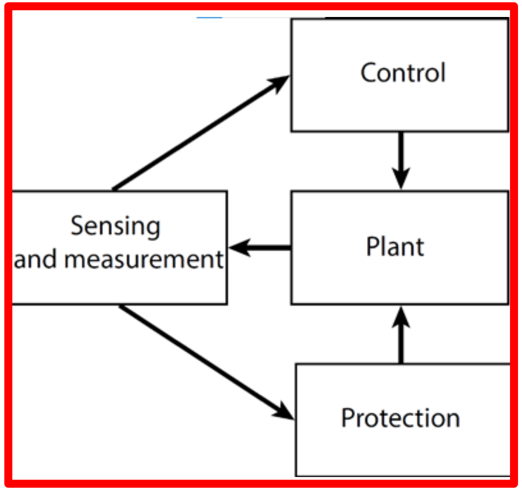
It depends

Source: Mankins 1995

State of the art

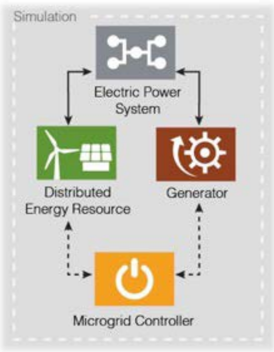
Electromagnetic transients simulation





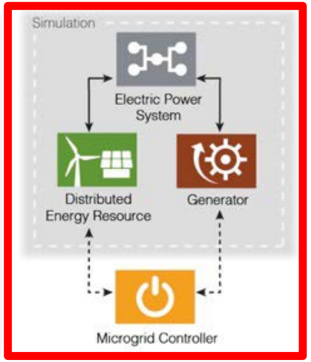
Evaluation Approaches Used in the Industry

A) Pure simulation



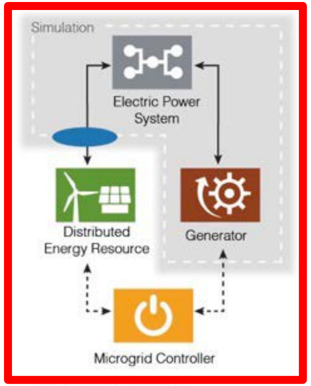
A) Pure Simulation

B) Controller-hardware-in-the-loop



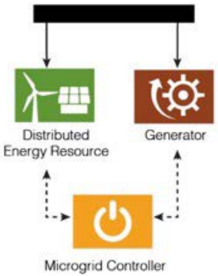
B) CHIL

C) Controller-hardware-in-the-loop and power-hardware-in-the-loop



C) CHIL & PHIL

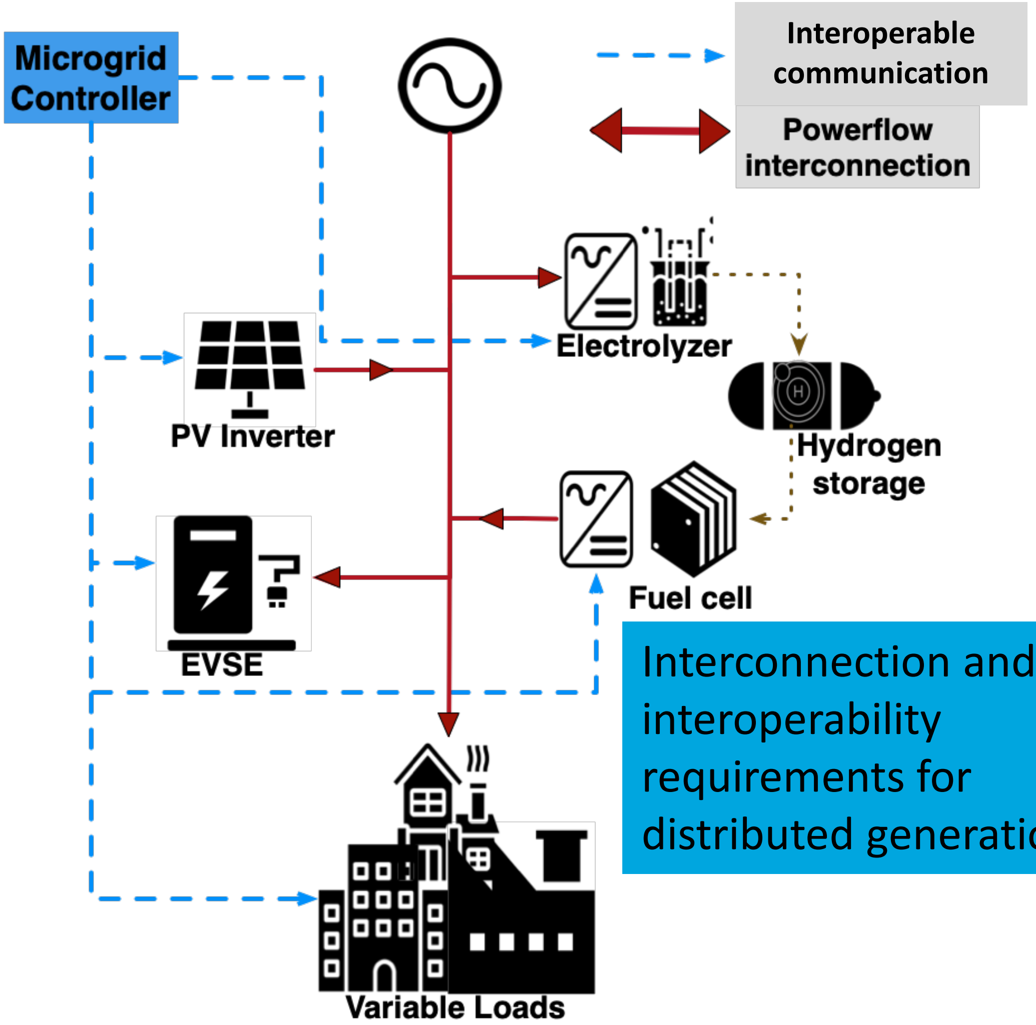
D) Hardware only



D) Hardware only

Source: Maitra 2007

Interconnection and interoperability of grid-forming fuel cell inverters



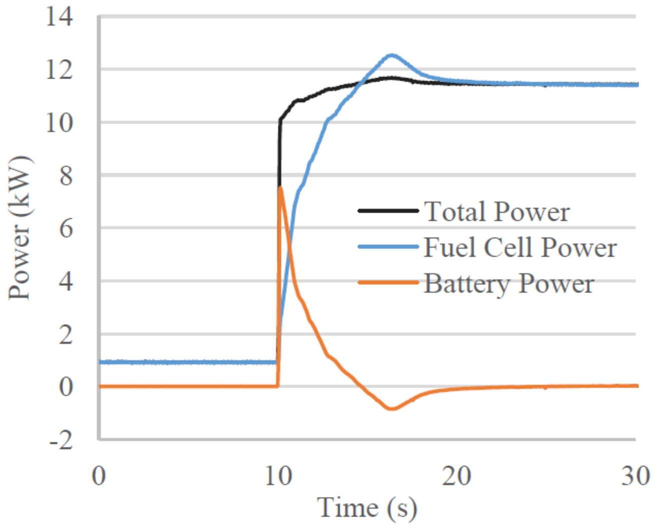
Interconnection and interoperability requirements for distributed generation

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.

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.

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.

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.

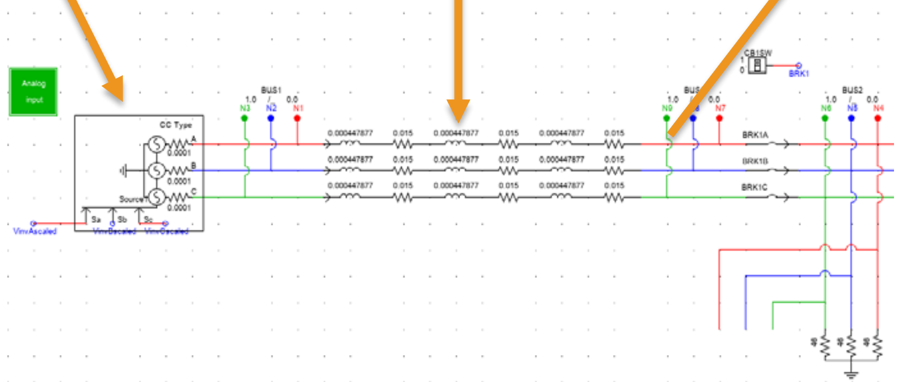
Power hardware

Grid forming inverter power hardware experiments and power hardware-in-the-loop experiments

Inverter

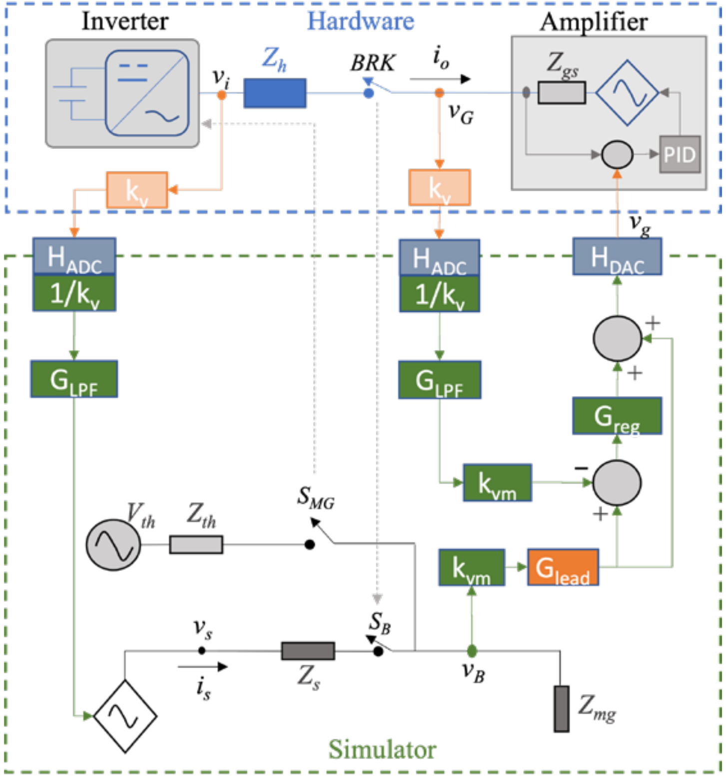
Inductor

Controllable supply



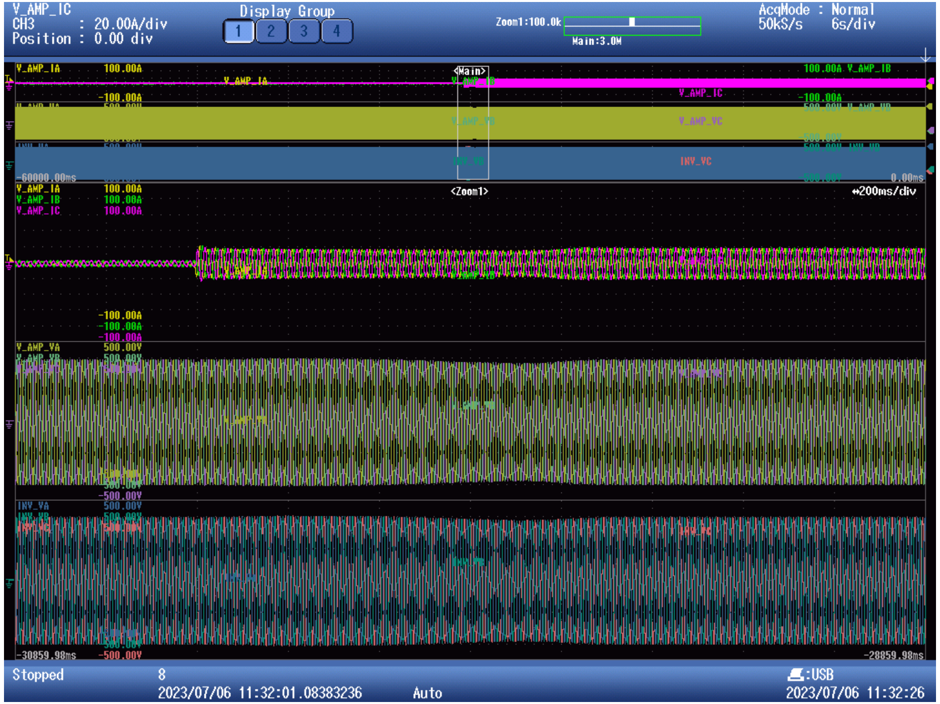
Power hardware-in-the-loop setup

Pratt, Annabelle, et al. "Power Hardware-in-the-Loop Interfaces for Inverter-Based Microgrid Experiments Including Transitions: Preprint." , Nov. 2023.

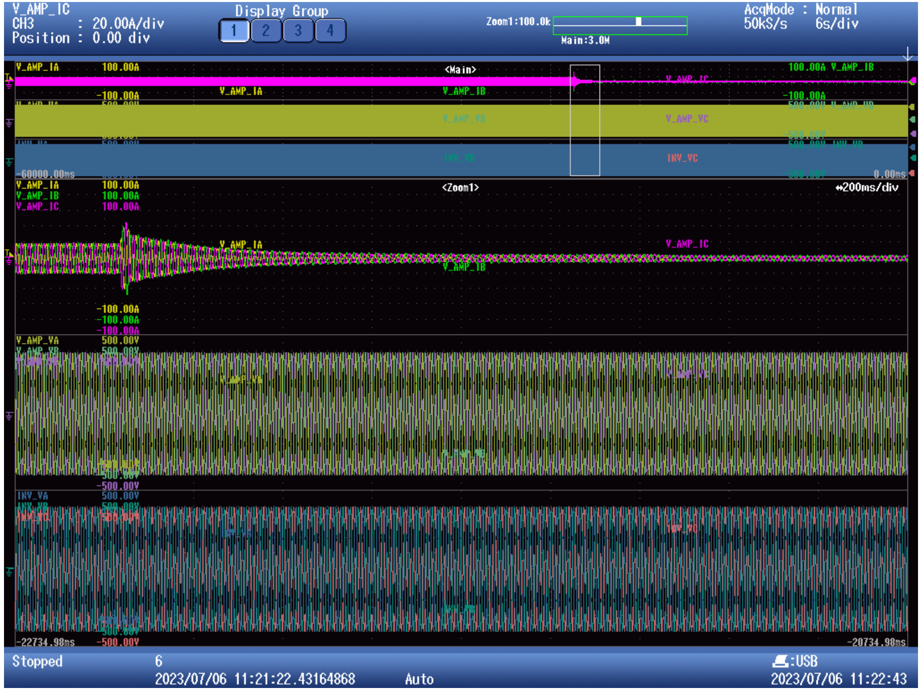


Source: Pratt 2023

Results

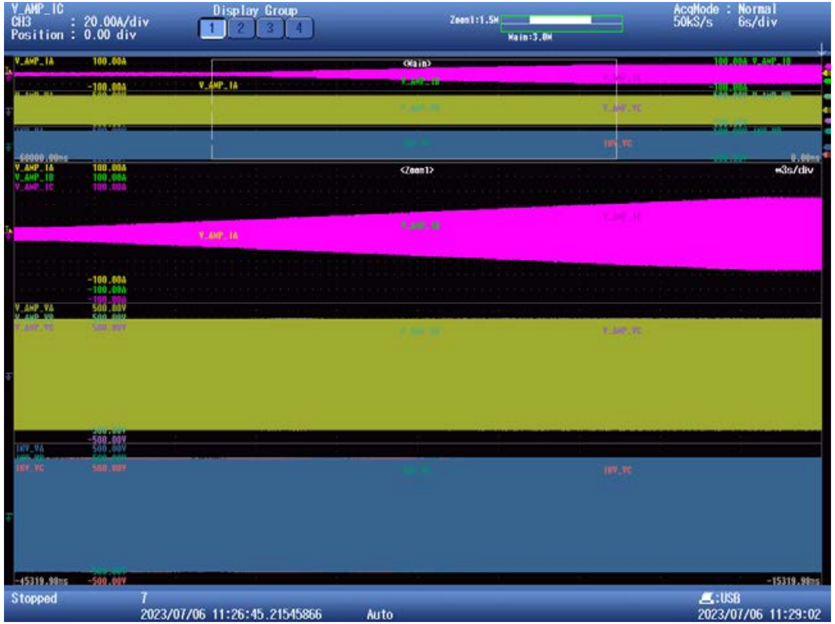


Grid-connected to islanded mode of operation

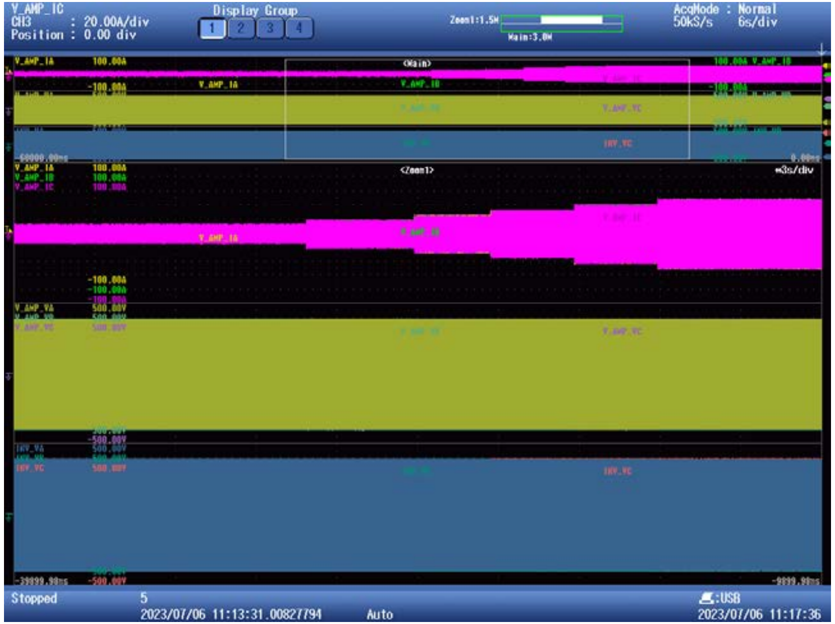


Islanded to grid-connected mode of operation

Results

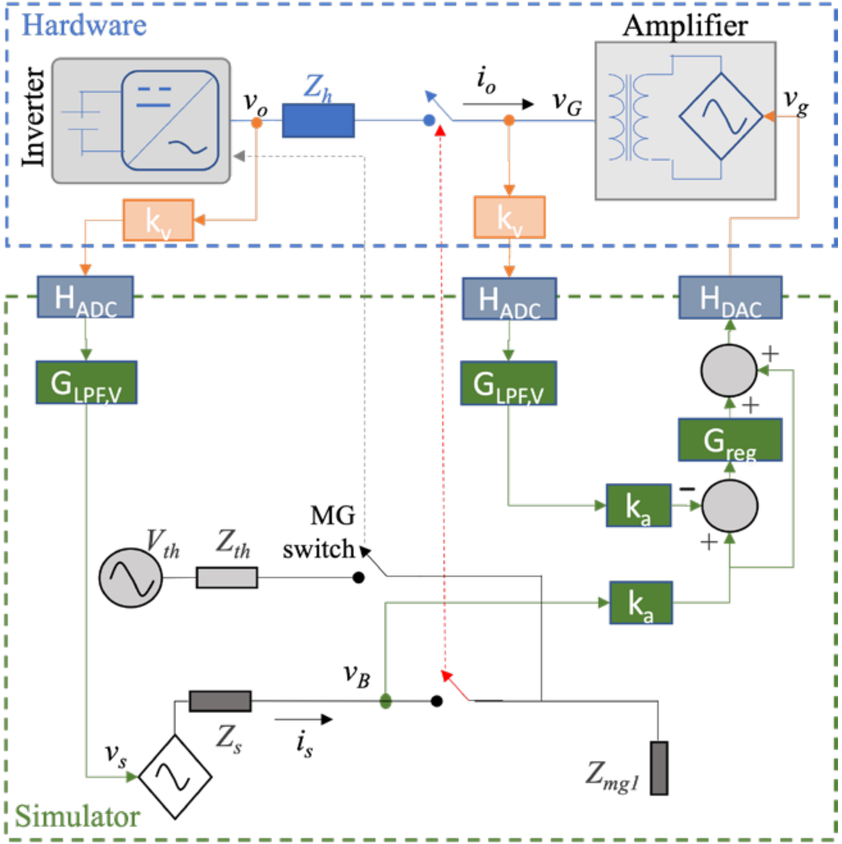


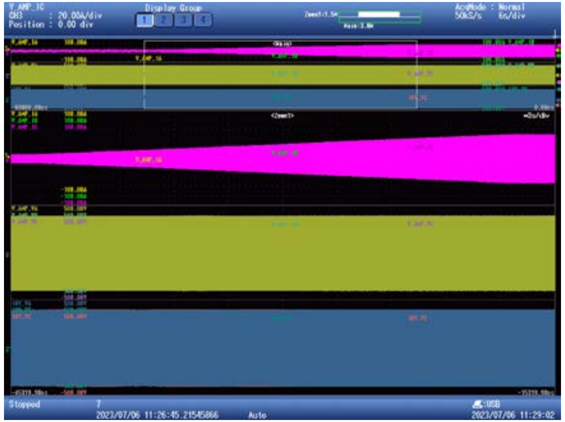
Grid-connected dispatch



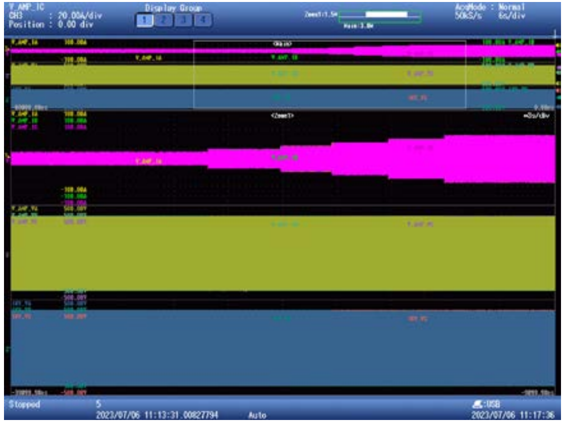
Islanded mode operation

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.

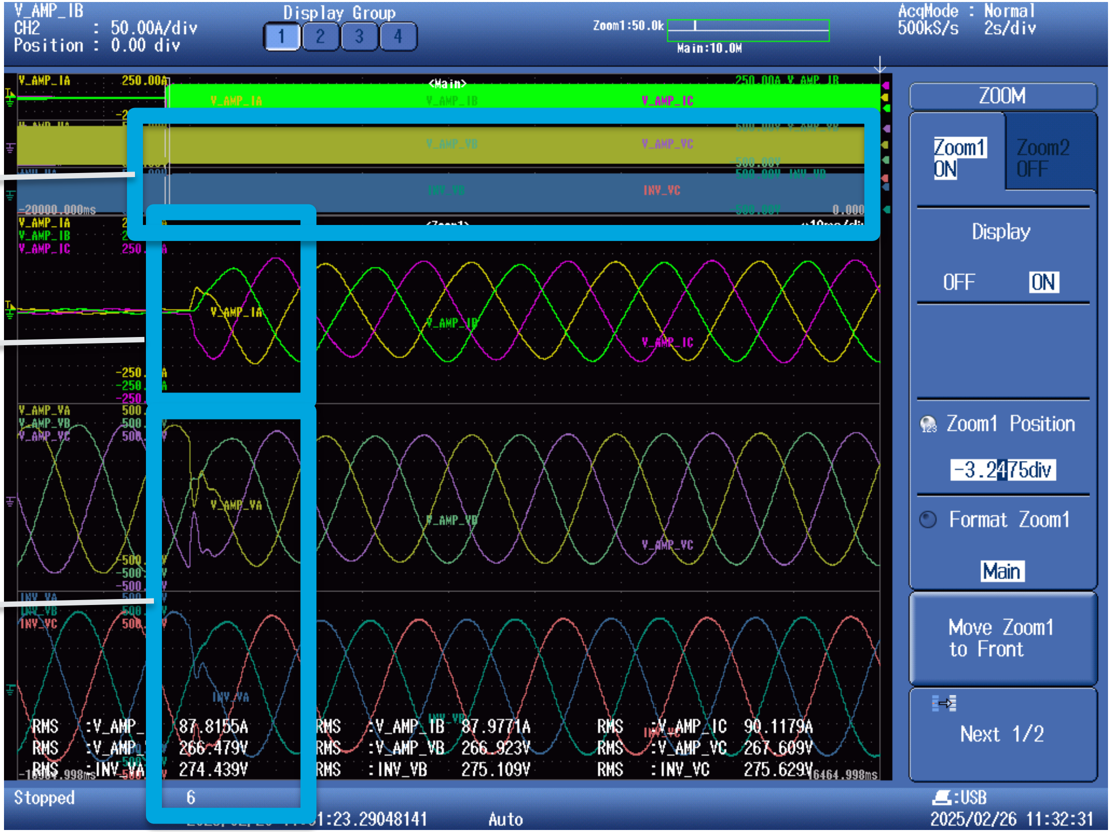
Data Center Microgrids

Load change from ~5 percent to ~85 percent of inverter rating

Consistent thickness and color of the plots indicate voltage magnitude and frequency is stable for prolonged time period

Current ramp up from 5 to 85 percent rating in less than one cycle (~16 milliseconds)

Minimal impact to voltage magnitude, frequency and phase



Load change from ~85 percent to ~5 percent of inverter rating

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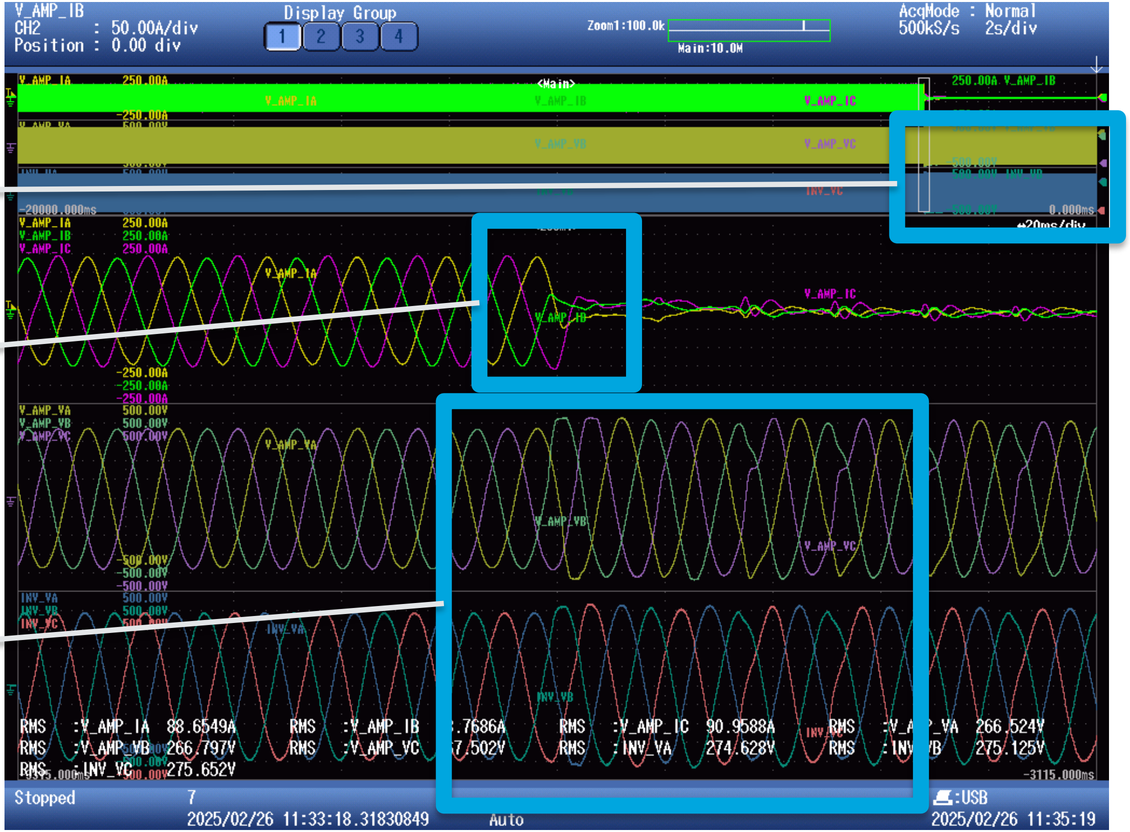
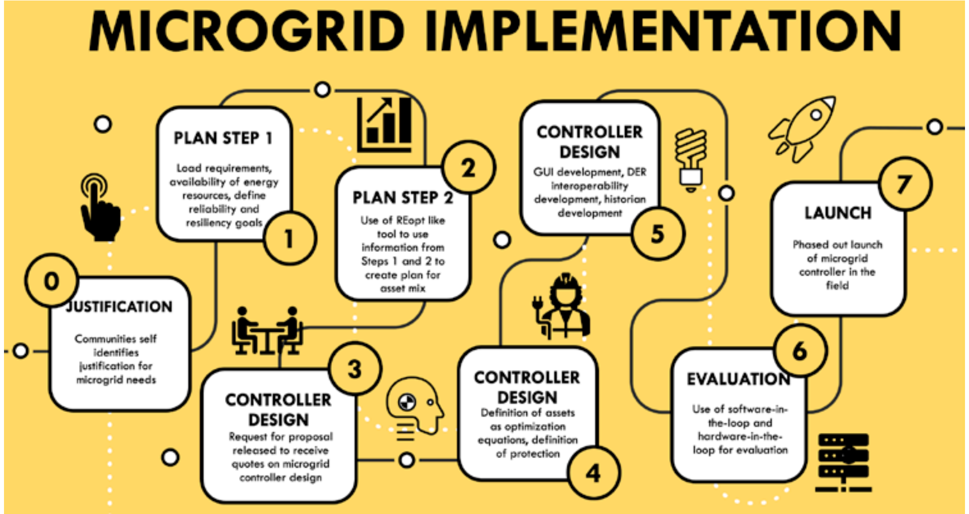
Current ramp up from ~85 to ~5 percent rating in less than one cycle (~16 milliseconds)

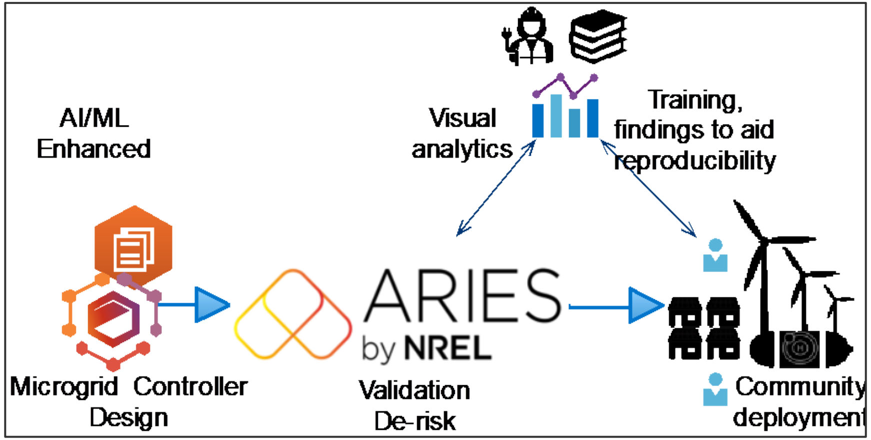
Minimal impact to voltage magnitude, frequency and phase



Future goals

- To standardize the steps that are taken after the design of the microgrid is completed and when the microgrid controller design is initiated.
- Currently forming industry advisory board.





References

Maitra, Arindam, Annabelle Pratt, Tanguy Hubert, Dean Wang, Kumaraguru Prabakar, Rachna Handa, Murali Baggu, and Mark McGranaghan. 2017. ”Microgrid Controllers: Expanding Their Role and Evaluating Their Performance.” *IEEE Power and Energy Magazine*. https://doi.org/10.1109/MPE.2017.2690519.

Pratt, Annabelle, Kumaraguru Prabakar, Subhankar Ganguly, and Soumya Tiwari. "Power-Hardware-in-the-Loop Interfaces for Inverter-Based Microgrid Experiments Including Transitions." In 2023 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 537-544. IEEE, 2023.

Thank You

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