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Simulation of Grid-Forming Inverters (GFMIs) Dynamic Models using a Power Hardware-in-the-Loop Testbed.

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Sandia National Laboratories

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Outline

- Introduction & motivation.
- Power Hardware in the Loop (PHIL) brief overview.
- Low inertia PHIL testbed for GFMIs models.
- Description of Simulation Models of GFMI.
  - CERTS GFMI model.
  - DQ GFMI model.
- Description of experimental setups and discussion of results.
  - PHIL setup for three phase experimental tests.
  - PHIL setup for single phase experimental tests.
  - Experimental setup for commercial single-phase inverters.
- Conclusions.
- Q&A.

Introduction & motivation.

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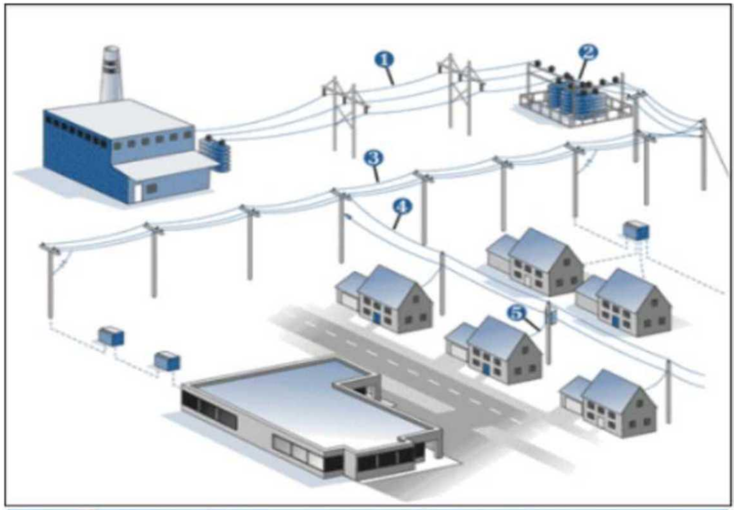
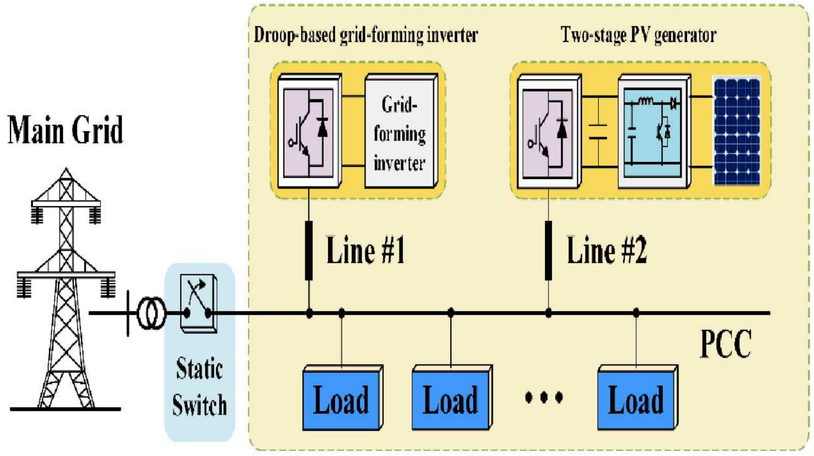
- Modern power grids around the globe are transitioning from radial to distributed.
- Most of Distributed Energy Resources (DERs) utilize electronic interfaces to interact with the grid.
- Recently, this interaction has not only been focused on supplying maximum available energy, but also on supporting the power grid under abnormal conditions (evolution of IEEE 1547).
- Grid-forming inverters (GFMIs) are gaining momentum as the penetration-level of DERs increases and system inertia decreases
- GFMIs tend to better preserve grid stability due to their intrinsic ability to balance loads without the aid of coordination controls



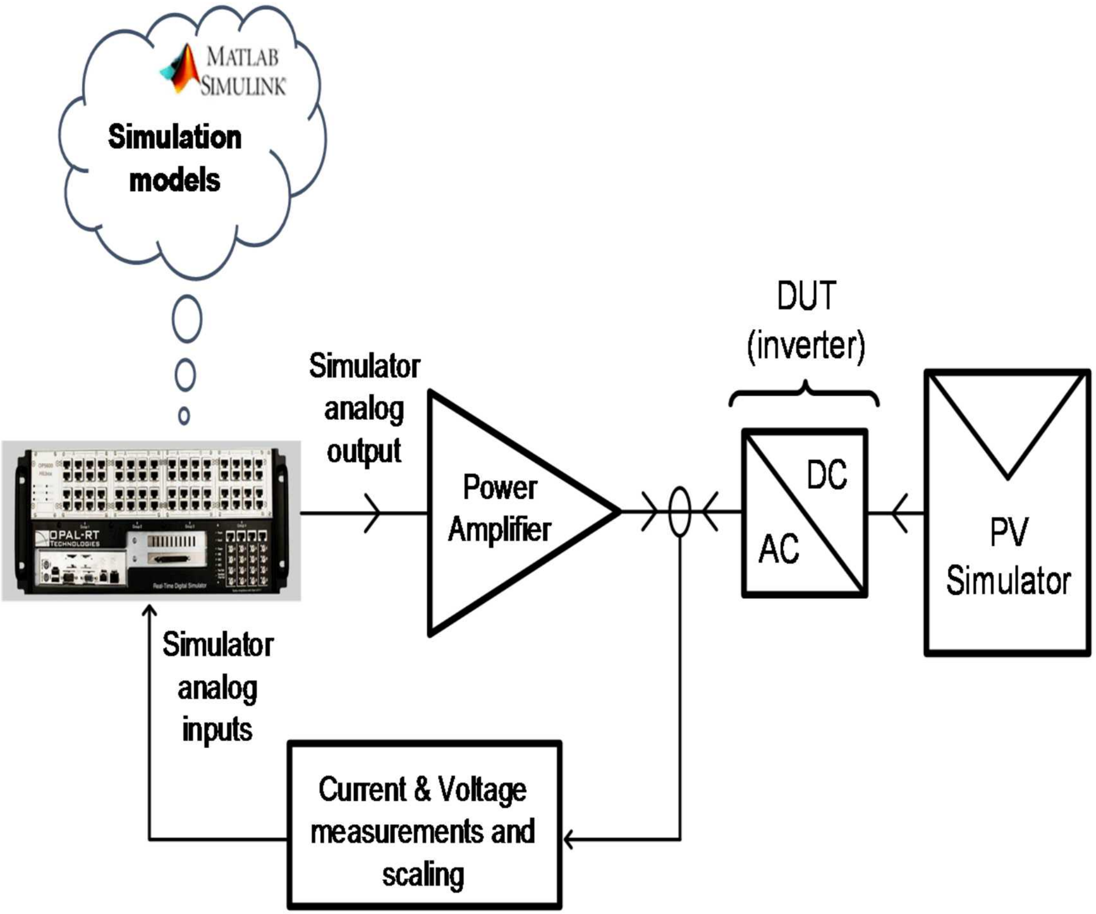
Introduction & motivation



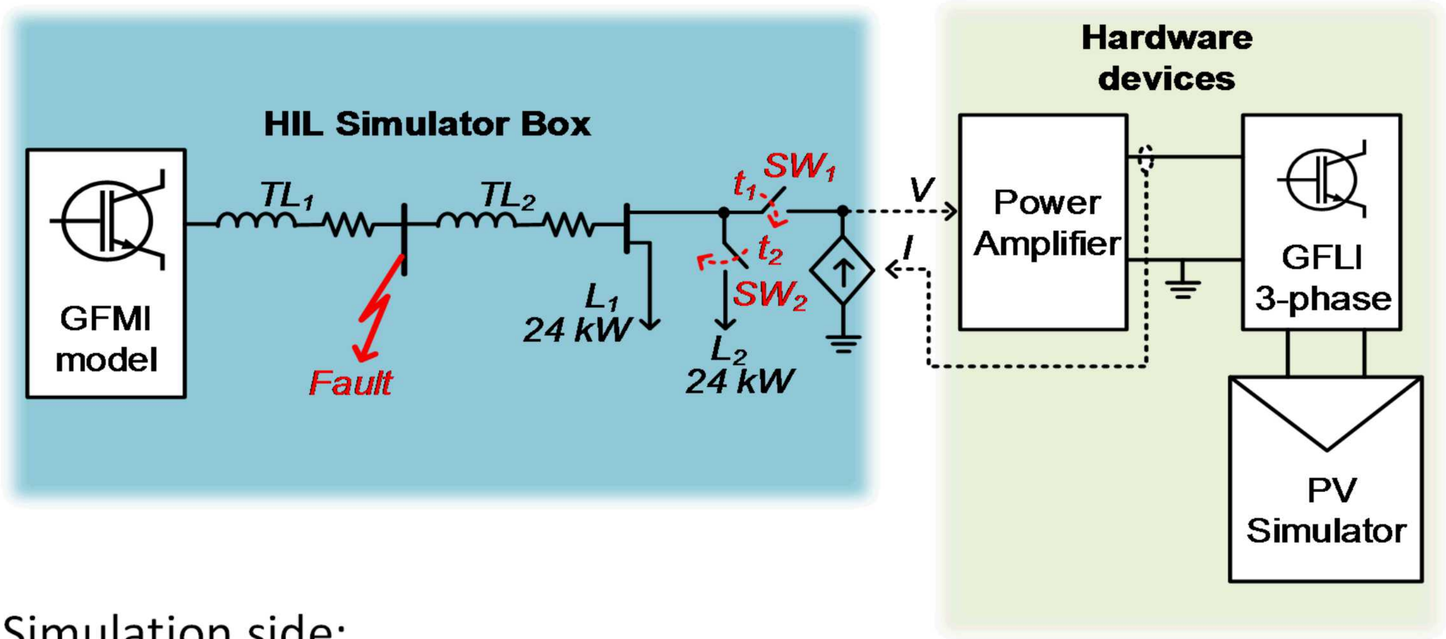
- Recently, a workshop related to GFMIs for low inertia power systems gathered members of academia, researchers of national laboratories, utility engineers, and representatives of inverter and protective relaying manufacturers.
- To date, almost all GFMI behavior and incident operational benefits have been shown in simulation. More research into hardware demonstration is needed.
- While demonstration of GFMI in application environments is ideal, it is difficult to tractable test hardware in a wide variety of operation conditions .
- Power Hardware-In-Loop (PHIL) is a flexible, high fidelity extension of simulation results that are more tractable to implement for a wide variety of operating conditions than a pure hardware testbed.

PHIL brief overview.

- Advances in parallel computing have allowed the proliferation of state-of-the-art real-time simulators (RTS).
- RTS provide the means to implement a systematic process for testing a variety of devices, including power converters.
- Experiments were performed in the PHIL testbed located at the Distributed Energy Technologies Laboratory (DETL) at Sandia National Laboratories.



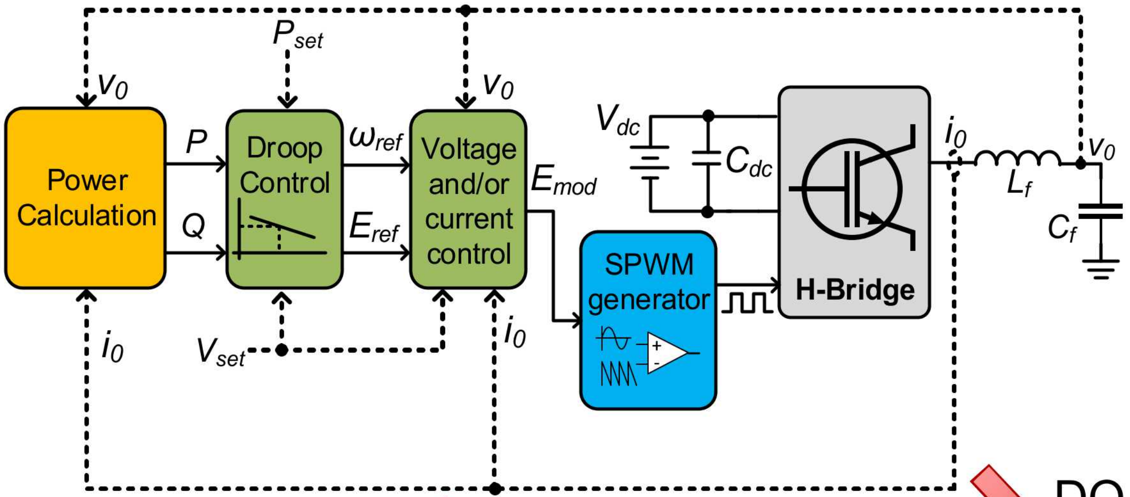
Low inertia PHIL testbed for GFMIs models.



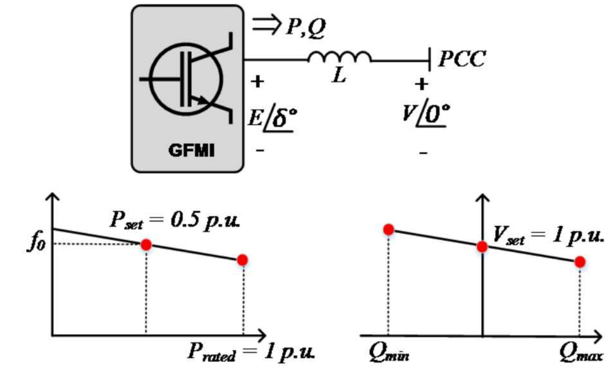
- Simulation side:
  - GFMI models under test.
  - Two transmission lines with high X/R.
  - Two 24 kW loads with their respective switches.
- Hardware side:
  - Commercially available grid-following inverter (GFLI) connected to a PV-simulator.

Description of Simulation Models.

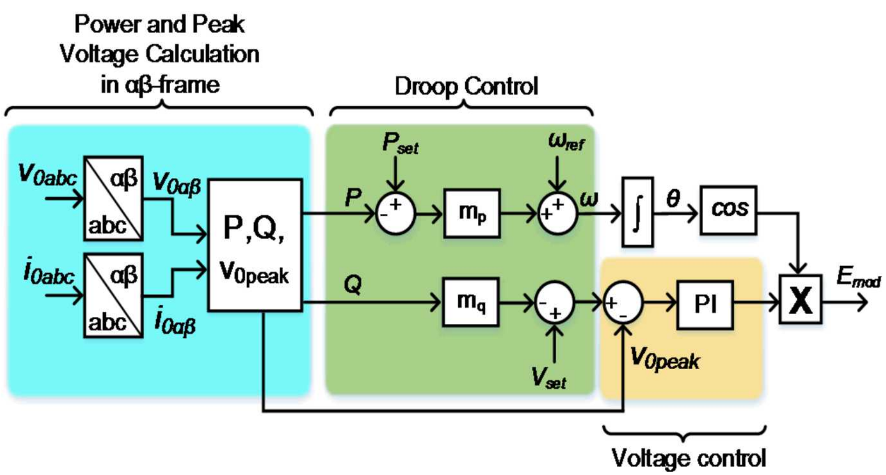
Generic GFMI model



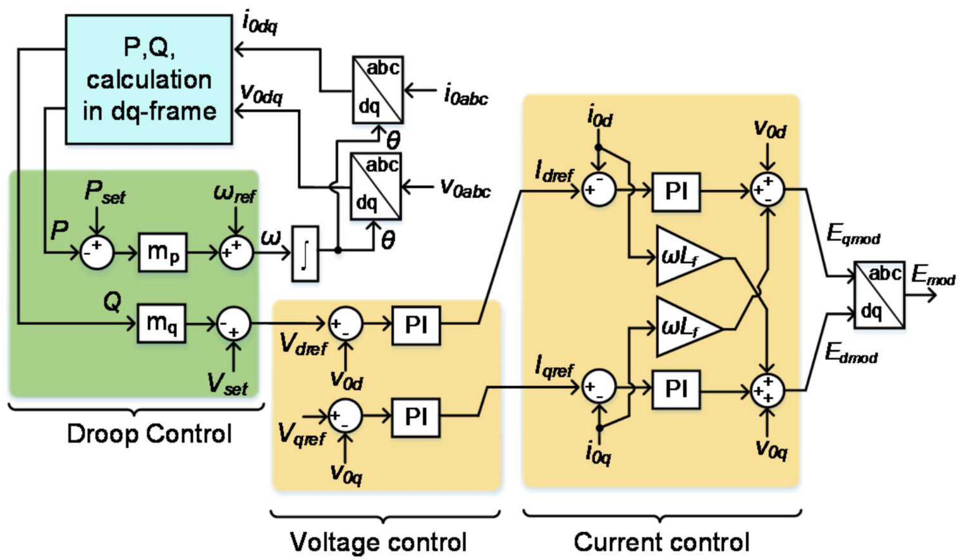
Droop characteristics



CERTS

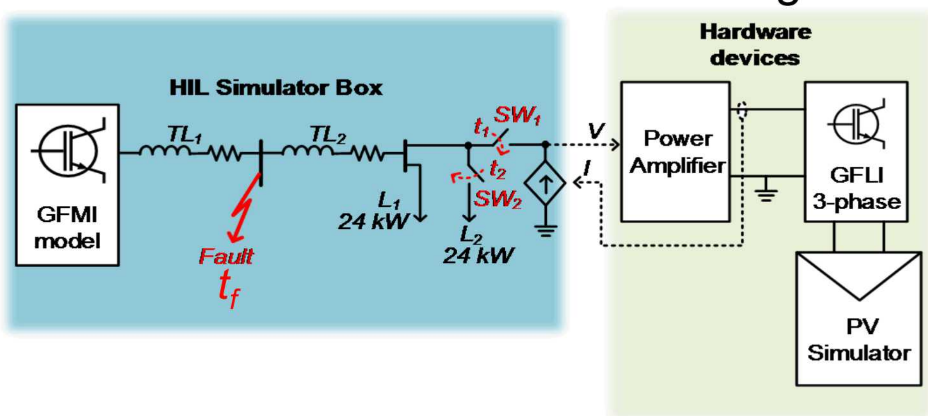


DQ

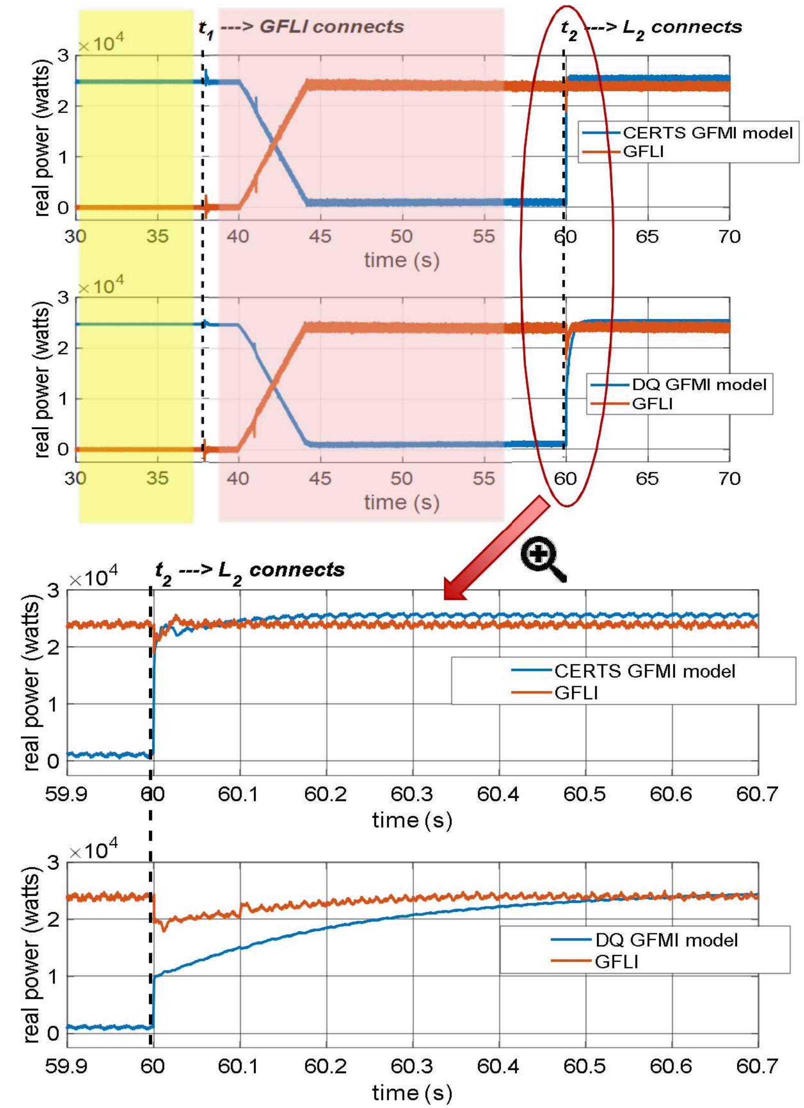


3-phase experimental PHIL setup and results.

GFLI connection and load change

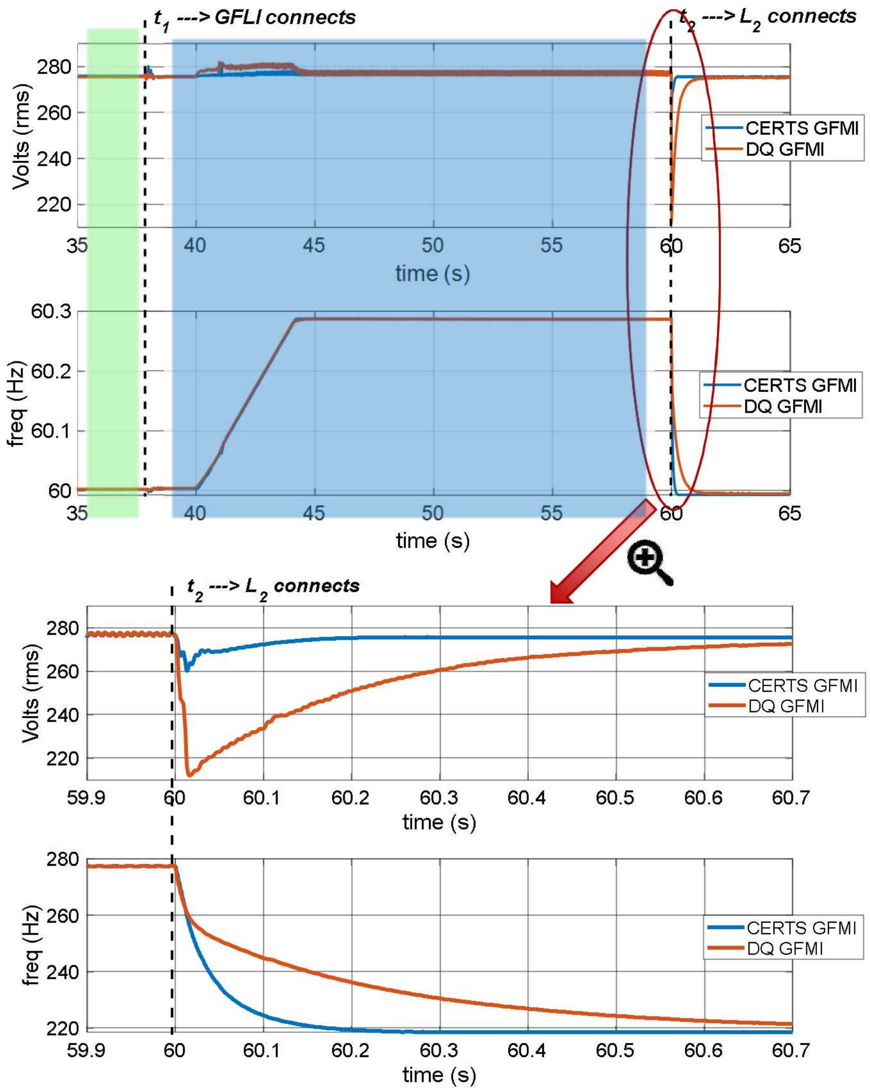


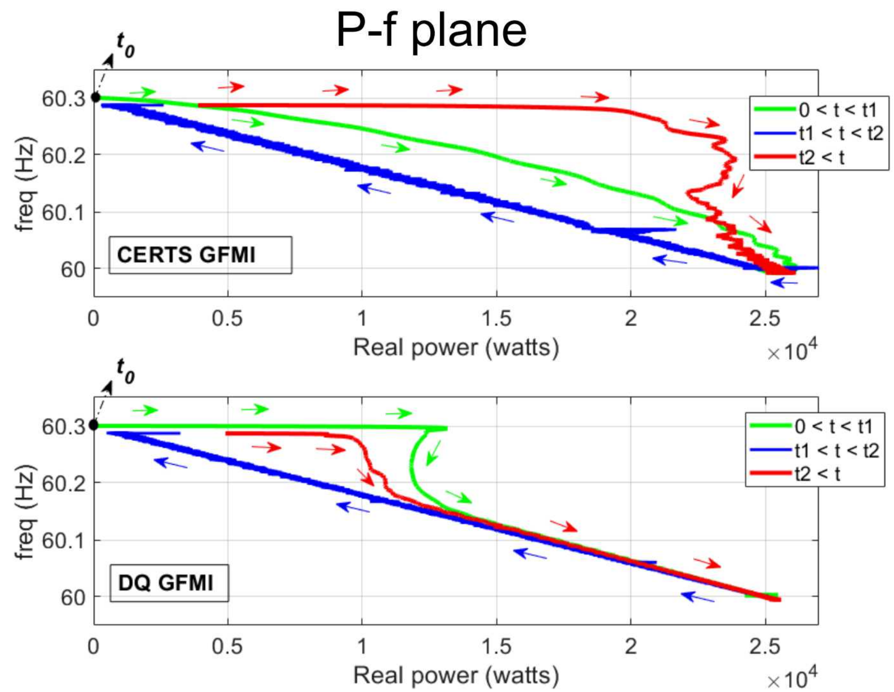
Real power dynamics



- Each GFMI model was simulated separately, thus a comparison of the dynamics can be made.
- Chronology of the simulation events.
  1. Before t_1, both switches are open and the GFMI model supplies L_1.
  2. At t_1, SW_1 closes allowing the GFLI to connect via PHIL.
  3. At t_2, SW_2 closes and connects L_2 to the system.

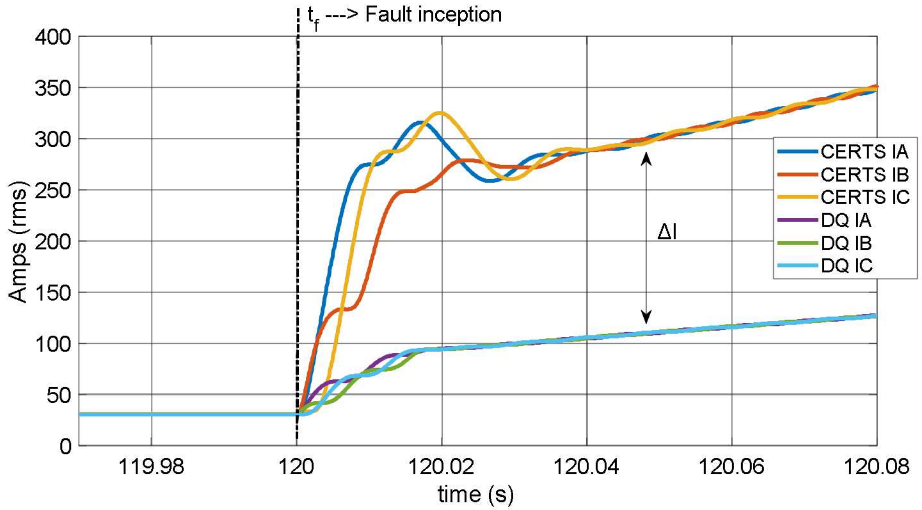
3-phase experimental PHIL setup and results. More on load change dynamics (Voltage & Frequency)

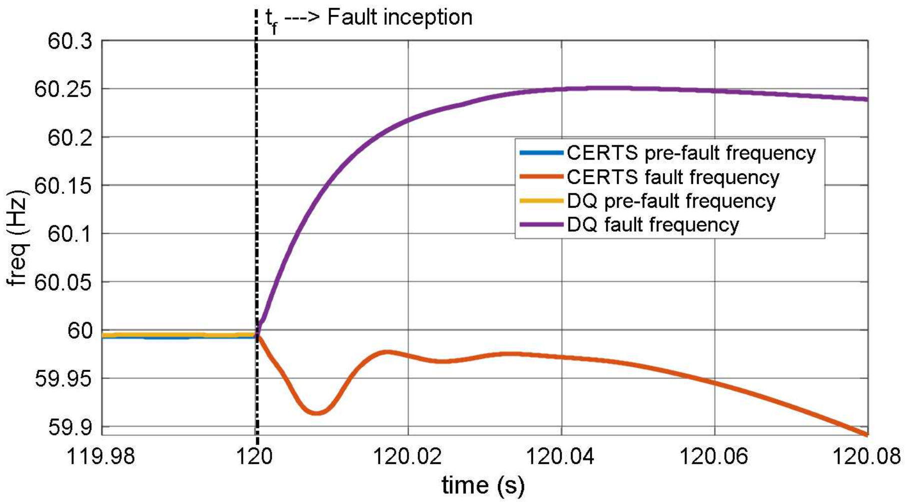




- Frequency curves follow the real power dynamics due to the linear relationship.
- Abrupt transitions cause deviation from the P-f droop characteristic.

3-phase experimental PHIL setup and results. Dynamics under a 3-phase fault.

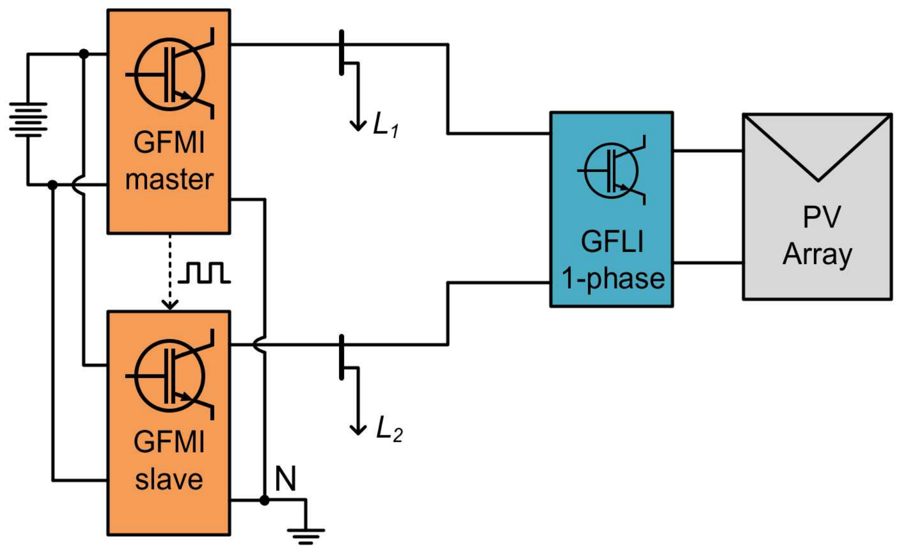




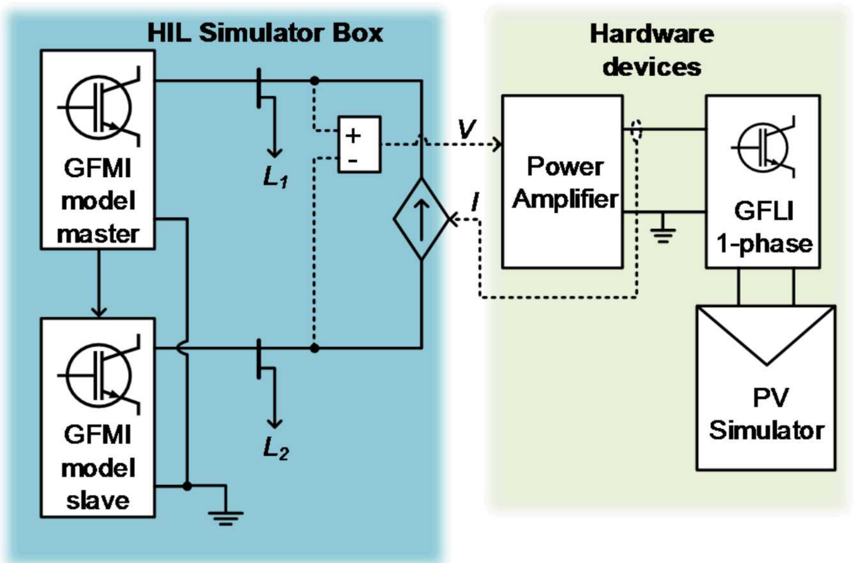
- The lower fault current contribution from the DQ GFMI is due to its intrinsic current regulation scheme.
- The parameter ΔI reveals a current difference of about 200 Arms between the two fault current contributions.
- This current difference must be taken into account when designing the protection scheme for this system.
- The frequency plots illustrate how the control scheme mandates the behavior of the GFMIs during the presence of a fault

Single-phase experimental PHIL setup and results.

NMSU Solar Station

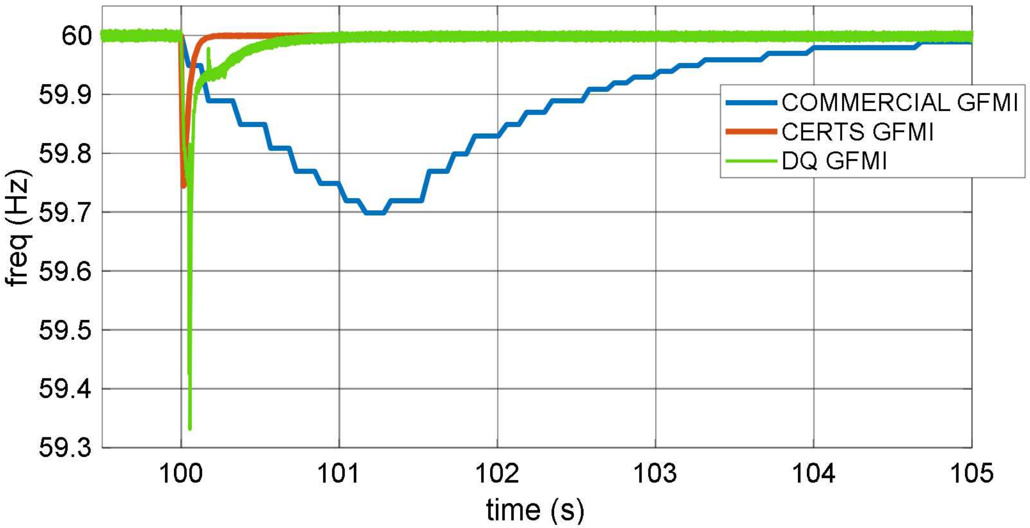


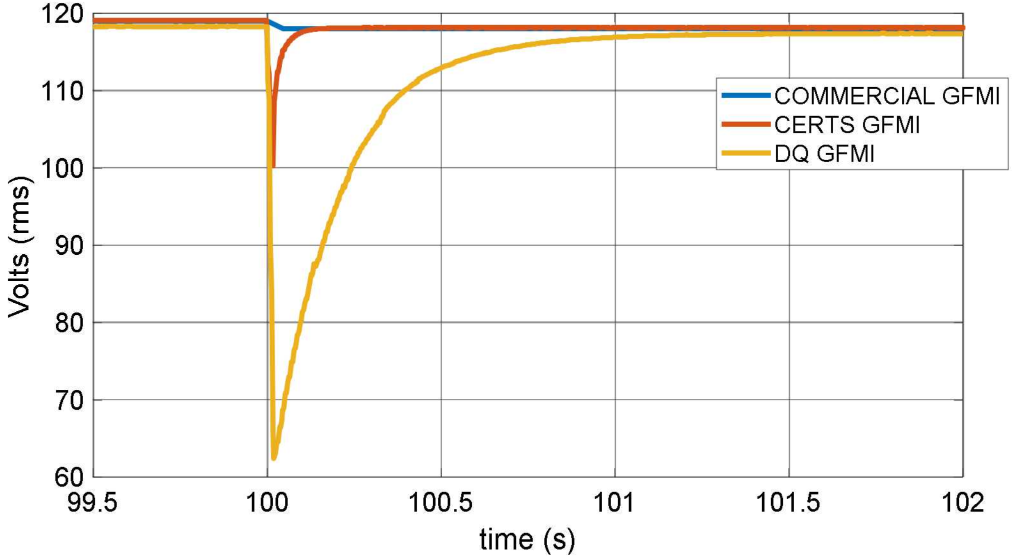
PHIL testbed at SNL



- This experimental testbed is located at the Southwest Technology Development Institute (SWTDI) at New Mexico State University. Master-slave configuration in split-phase with a GFLI (2 kW)
- L_1 and L_2 are balanced loads (P=4.5kW, Q=1kVar).
- This system was replicated using the PHIL setup at SNL.
- *L1* and *L2* were simultaneously connected to the system as shown in both figures

Single-phase experimental PHIL setup and results.





- The frequency spike is similar in magnitude for the commercial inverter and the CERTS model, but the response of the CERTS is significantly higher.
- DQ model showed large spikes in frequency and voltage due to the slow response imposed by two control loops.
- In steady state the two simulation models and the commercial inverter converge to the same value.

Conclusions.

- A low inertia PHIL testbed was introduced to perform the different testing scenarios for GFMIs.
- The dynamic behavior of two simulation models of grid-forming inverters are evaluated in terms of transient and steady-state stability under abrupt load changes and low impedance faults.
- Simulation results showed that a GFMI model with DQ current control shows an intrinsic slower response of frequency and voltage regulation when compared to the response of a CERTS GFMI model.
- Under fault scenarios, the DQ controlled GFMI performed better in terms of limitation of fault current contribution due to its inherent current control scheme.
- The single phase models were validated against a commercially available inverter.
- In the single phase case validation, the PHIL results showed accurate results in steady state, but further research and experiments are required to validate the corresponding differences between experimental and PHIL results during transients (inconsistencies in voltage and frequency spikes).

QUESTIONS?

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