Alaska St Mary's: A Case Study in Advanced Power Electronics

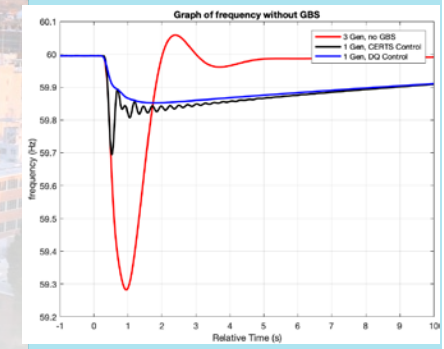
2020 Microgrid R&D Program

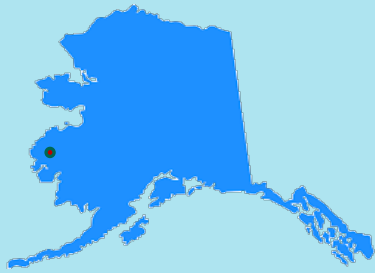
Peer Review Meeting

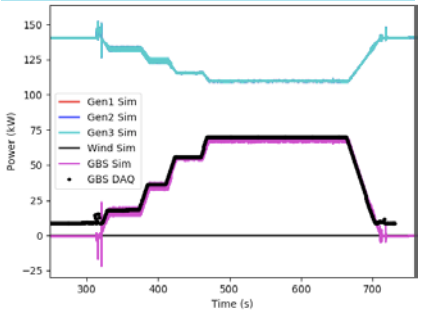
June 09, 2020

Jack Flicker

Sandia National Laboratories







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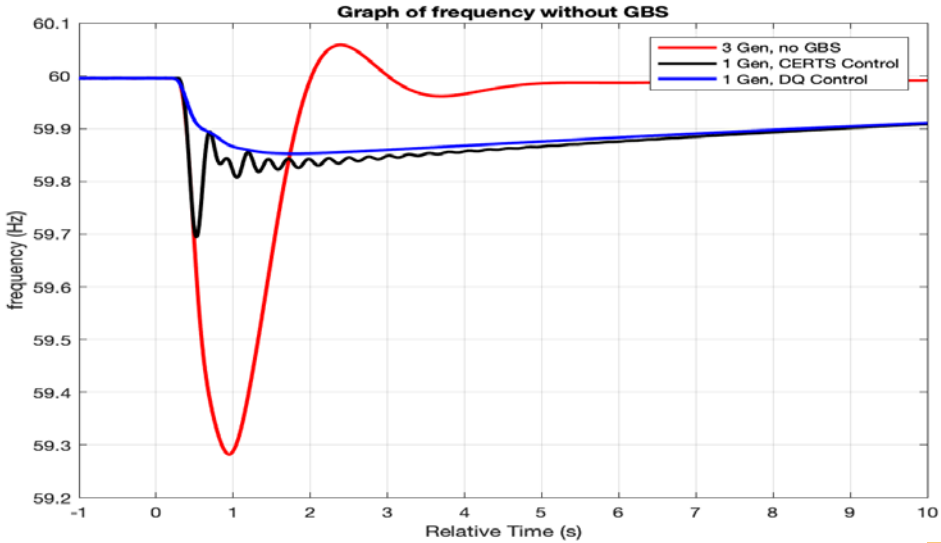
Alaska St Mary's: A Case Study in Advanced Power Electronics

Objectives & Outcomes

High fidelity models for the St. Mary's system are being evaluated and extended through the incorporation of a grid forming inverter providing spinning reserve in a power hardware-in-loop setup to capture transient behavior and stability of a real grid forming inverter operating in the simulated St. Mary's system.



Technical Scope

To validate the simulations carried out in previous years of the St. Mary's Project, an Opal RT real-time HIL platform is being utilized to give more realistic results for system behavior. A commercial grid forming inverter is being incorporated in the St. Mary's simulation to identify differences in dynamic behavior between a commercial GBS system and a simulated one.

Funding Summary ($K)

FY19 & prior, authorized	FY20, authorized	FY21, requested
500,000	500,000	

Project Partners

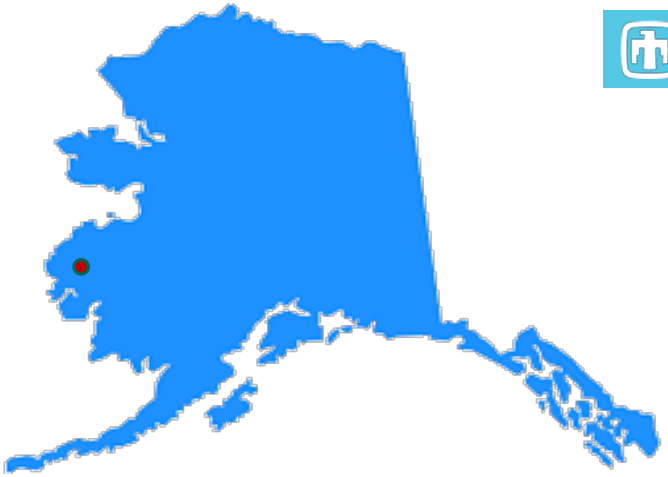
Alaska Village Electric Cooperative (AVEC)

- Provides electricity to members in 58 communities
  - >40% of Alaska village population
  - Village sizes from ~100 to ~1,000 customers (100 kW to 3 MW)
- None connected to a transmission grid
  - Power generated locally utilizing diesel electric generators
  - Wind (11) and solar power in a subset of communities
- Interested in replicating successful approaches microgrid systems
  - Reducing fuel consumption while increasing resiliency

Alaska Center for Energy and Power (Univ. of Alaska-Fairbanks)

- Power Systems Integration Lab
- On the same scale as a village power system
  - Emulates isolated hybrid-diesel grid at up to 500 kW
  - 480 VAC three-phase, up to 600A
  - Wind, diesel, and grid-forming emulators
  - Fault/contingency scenarios

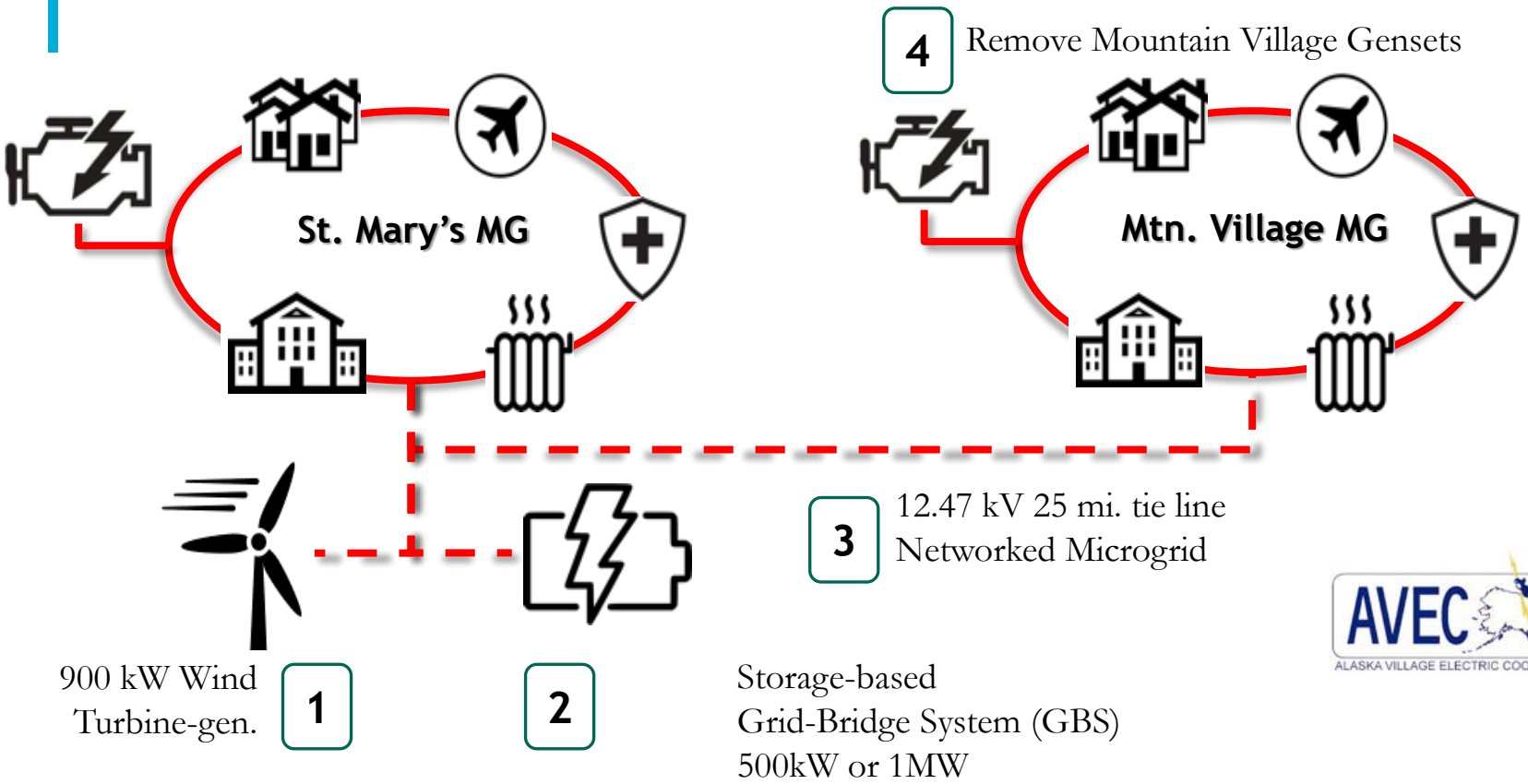
St. Mary's and Mountain Village, AK



Energy Resilience Challenge:

- Both villages are rural islanded grids supplied by diesel gensets
- Diesel fuel shipped up Yukon River, impassable August-April
- Life threatening issues if diesel runs out during winter
  - Necessity for high reliability, low maintenance components
- High energy cost, >25% of average household income

St. Mary's and Mountain Village, AK

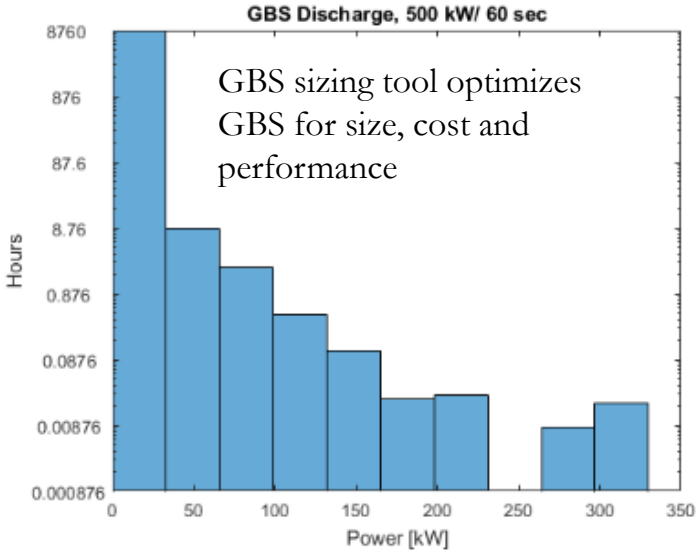


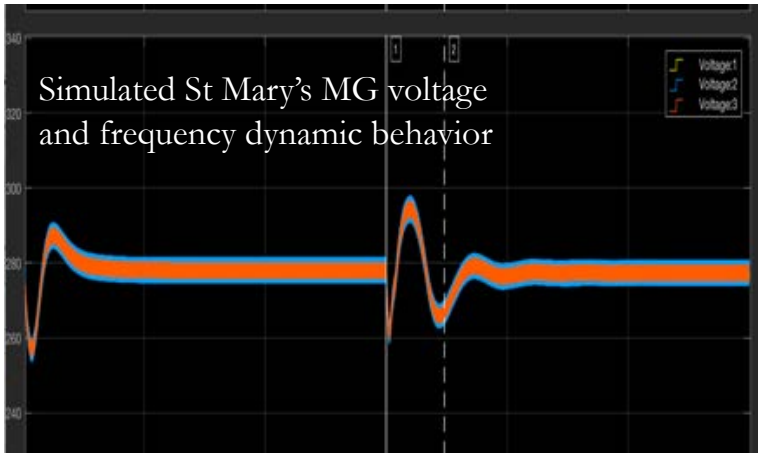
- Currently three diesel gensets (499 kW to 908 kW)
- Three-stage plan to lower costs and increase reliability and resilience
  1. Wind turbine-generator to reduce fuel use (DOE/IA)
     - EWT 900 kW Type IV pitch-controlled wind turbine generator **Currently Operational**
  2. Storage-based grid bridge system (GBS) for spinning reserve (DOE/OE + DOD/ONR)
     - Battery Energy Storage + Grid Forming Inverter **Procurement Underway**
  3. Network St. Mary's MG with Mountain Village MG via 12.47 kV tie-line **Currently Commissioning**

Significance and Impacts

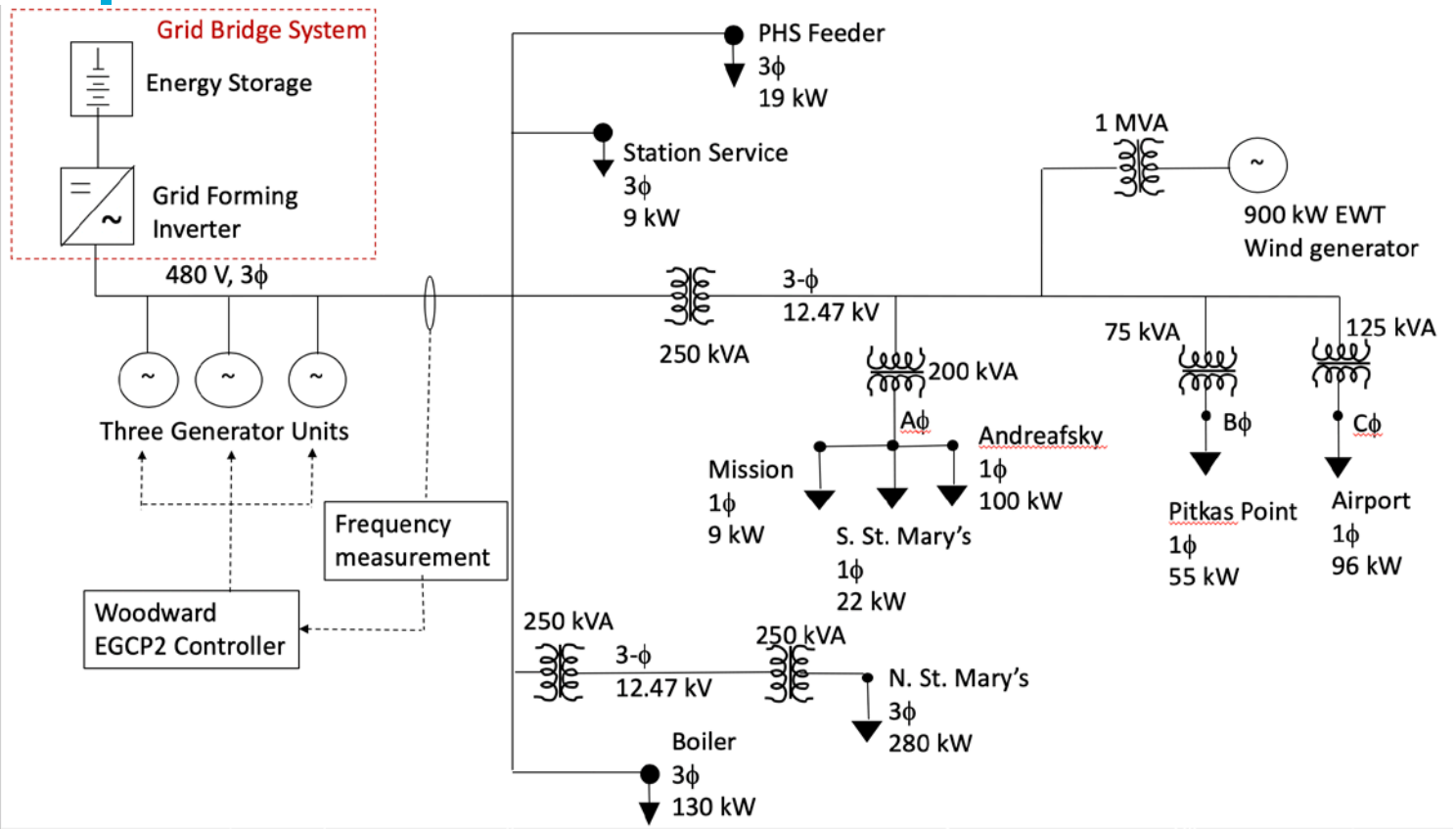
- Sandia , AVEC, and ACEP partnering to study and demonstrate advanced renewable-based microgrids
- Planned outcomes:

1. Validated open-source models for RE-based networked MG, including grid-forming inverters
    1. Simulation and Hardware-in-loop
    2. Validated with PMU data and laboratory testing
2. Demonstration of replicable and sustainable energy resilience solution for **AK & beyond**
    - 6 potential AK locations identified
    - Transition to rural distribution systems with high renewable content and power quality issues
    - Application of grid forming inverters for high-consequence and high-resilience microgrids
3. Open-source GBS optimal sizing tool for microgrid implementation
    1. Energy balance and dispatch optimization for Microgrids
4. Identification of technology, standards and workforce gaps relevant to the deployment of islanded and grid-connected networked microgrids
    1. Evaluation of required behavior and settings for grid forming inverters to improve power quality



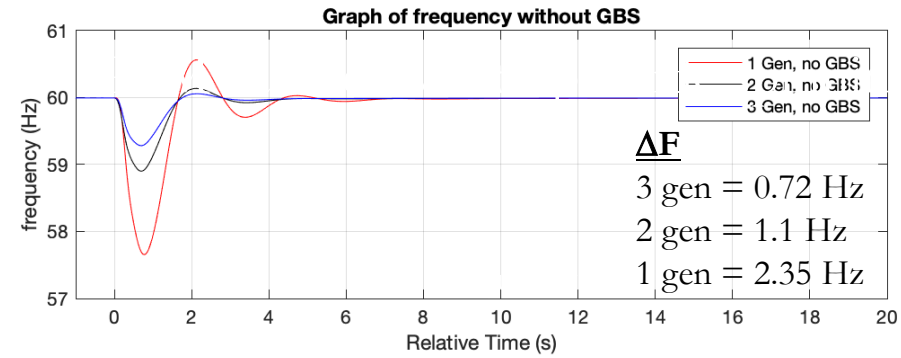


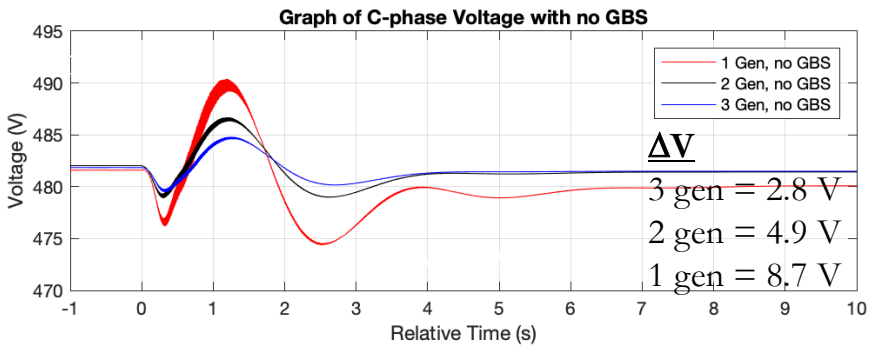
Open-source models for RE-based networked MG

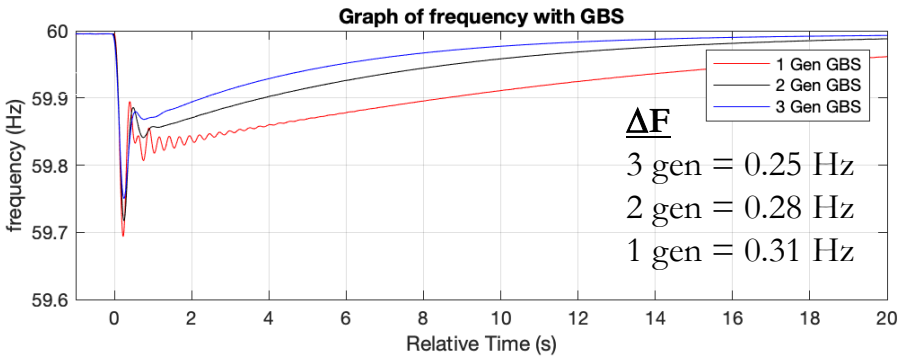


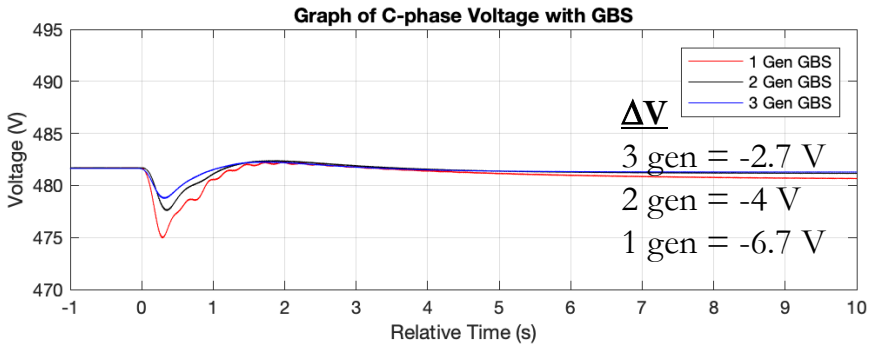
- Developed full Matlab Simulink model for the St. Mary's microgrid
  - includes developed models for diesel
  - Type IV wind turbine
  - Grid Bridge System
- System size based on average winter high consumption, provided by AVEC
  - Mix of 3 ϕ and 1ϕ loads
  - Voltage imbalance of ~5%
- Implemented on Real Time simulator (Opal RT)
  - Allows for Hardware-in-loop testing

Evaluated GBS ability to provide spinning reserve for loss-of-wind scenario





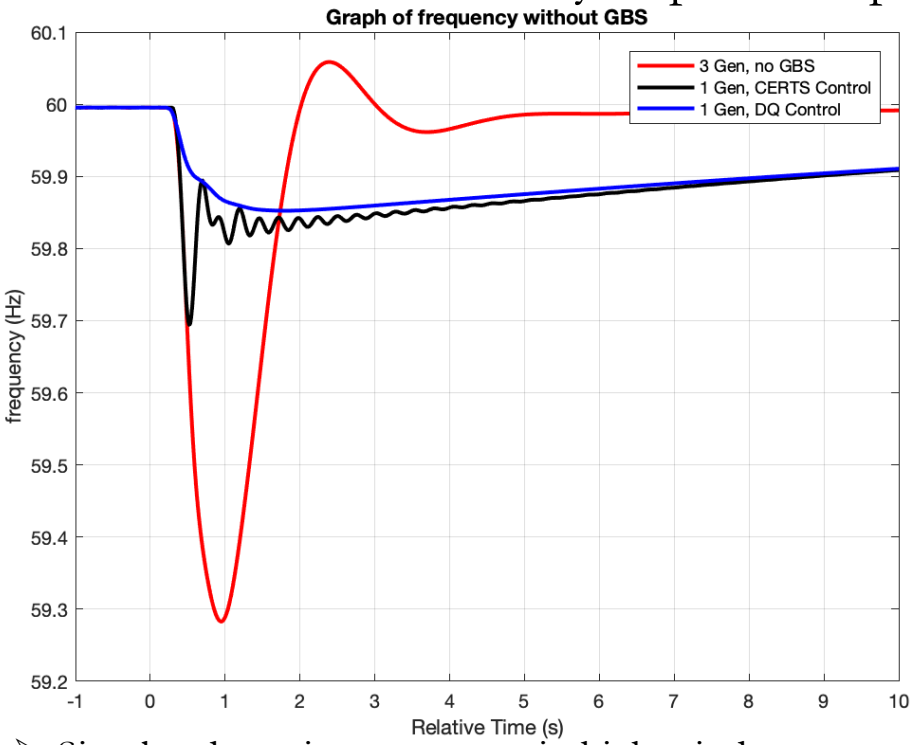


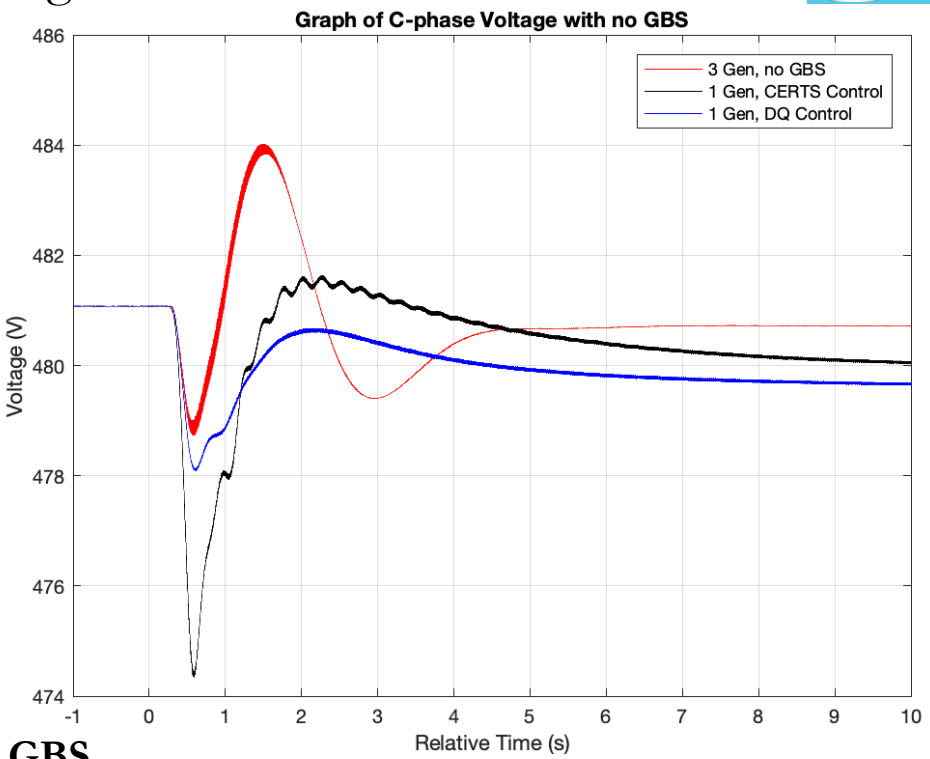


- Simulated contingency event in high-wind system with **No GBS**
  - Instantaneous wind penetration from 85% to 15% in 2s
  - Compared situation with 1, 2, and 3, generators
    - Single generator can supply remaining load
    - Other generators lightly loaded to supply spinning reserve

- Significant deviations in voltage and frequency with only 1 genset
  - Deviations significantly reduce as more generators are added

Evaluated GBS ability to provide spinning reserve for loss-of-wind scenario





- Simulated contingency event in high-wind system **with GBS**
- GFM results in better frequency and voltage response
  - GBS + 1 generator outperforms even 3 generator case without GBS
  - Reduces necessary genset ramp rate (not shown)
  - Fuel savings from reduced number of generators and slow ramp rates

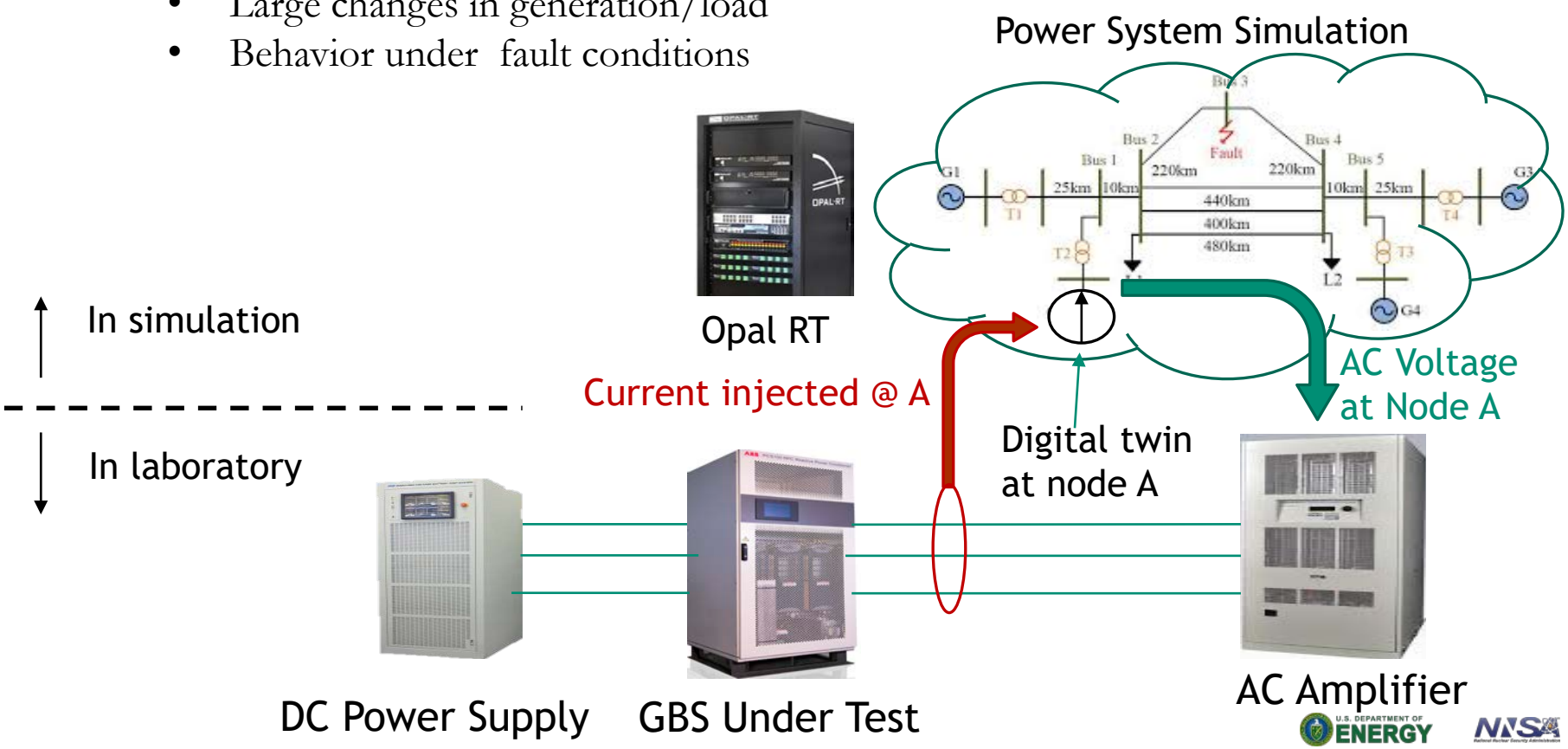
- Evaluated variety of control mechanisms for grid forming inverters (GFM)
  - Similar results for reduced frequency and voltage deviations in systems
  - Secondary effects on voltage/frequency due to controls

- Results will be presented at Power and Energy Society General Meeting in August
- Journal article submitted to *Energies*

Power Hardware in Loop of GFM

- Simulation of St. Mary's system shows benefits of GBS incorporation
  - Demonstrated Spinning reserve operation for variety of control schemes

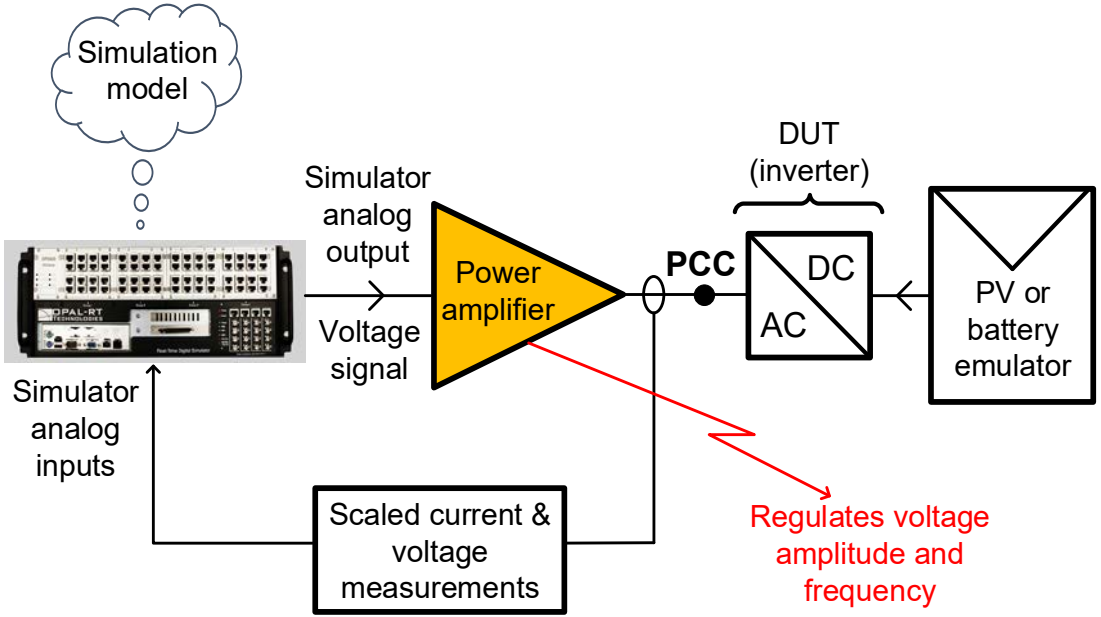
- Next step is incorporating GBS into simulation in power hardware in loop (PHIL) setup
  - More realistic behavior for power electronic devices
  - Especially under saturation (nonlinear) conditions typically of contingencies
    - Large changes in generation/load
    - Behavior under fault conditions



Power Hardware in Loop of GFM

- PHIL simulation setups for traditional Grid Following Inverters (GFLIs) are well documented
- However, the interfacing of Grid Forming Inverters (GFMs) into **closed-loop** PHIL simulation setups is lightly documented
  - Some work on open-loop implementations
  - GFM + grid simulator with no simulation component
    - Much work done in certification of grid forming inverters
    - For example, simulating pre-set voltage droop with grid simulator

- For GFM, direct connection with power amplifier *can lead* to instability → catastrophic damage
  - Both devices inherently try to regulate the voltage and frequency at their own settings
  - Lack of angle synchronization between the two devices



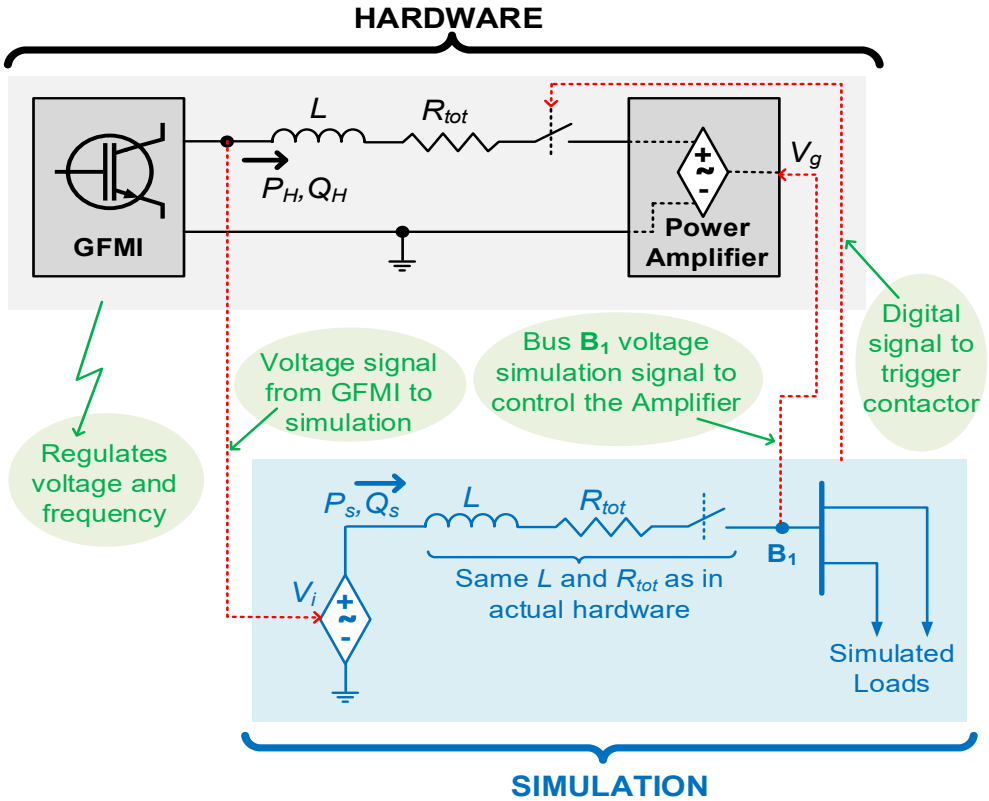
We have developed a method to interface GFM with simulation in PHIL

Regardless of GFM internal control (e.g. in isochronous mode)

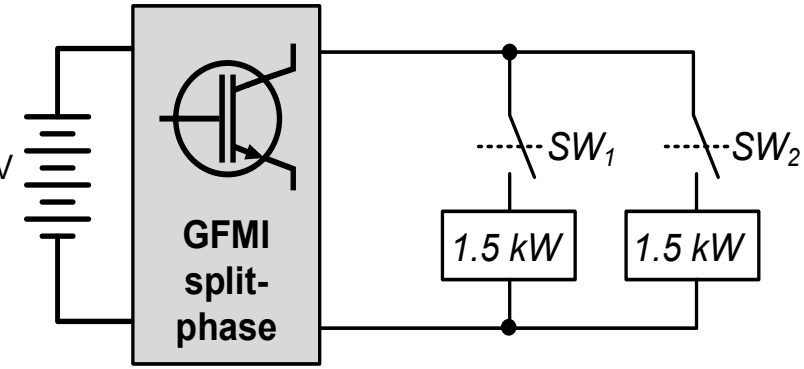
Power Hardware in Loop of GFM

- Proposed method:
  - Inductor placed between GFM and power amplifier
  - Inductor and total resistance of hardware replicated inside the simulation
  - In simulation voltage measured at GFM replicated in controlled voltage source V_i
  - Power amplifier emulates voltage at bus B1

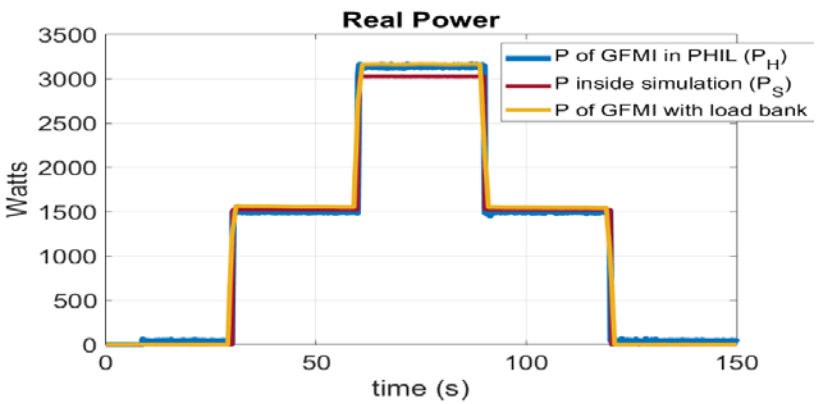
- Contactor controls interconnection of amplifier and GFM devices
  - Triggered by a digital signal from real time simulator at minimum of phase angle
    - Ensures correct synchronization
    - Minimizes inrush currents
    - Avoids instability issues previously mentioned



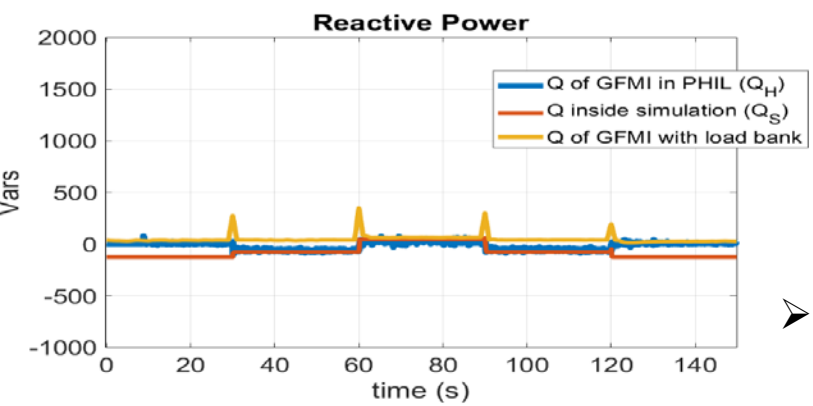
Power Hardware in Loop of GFM



- PHIL simulation of GFM with grid simulator
  - GFM does not have droop capabilities
  - Only operated in isochronous mode



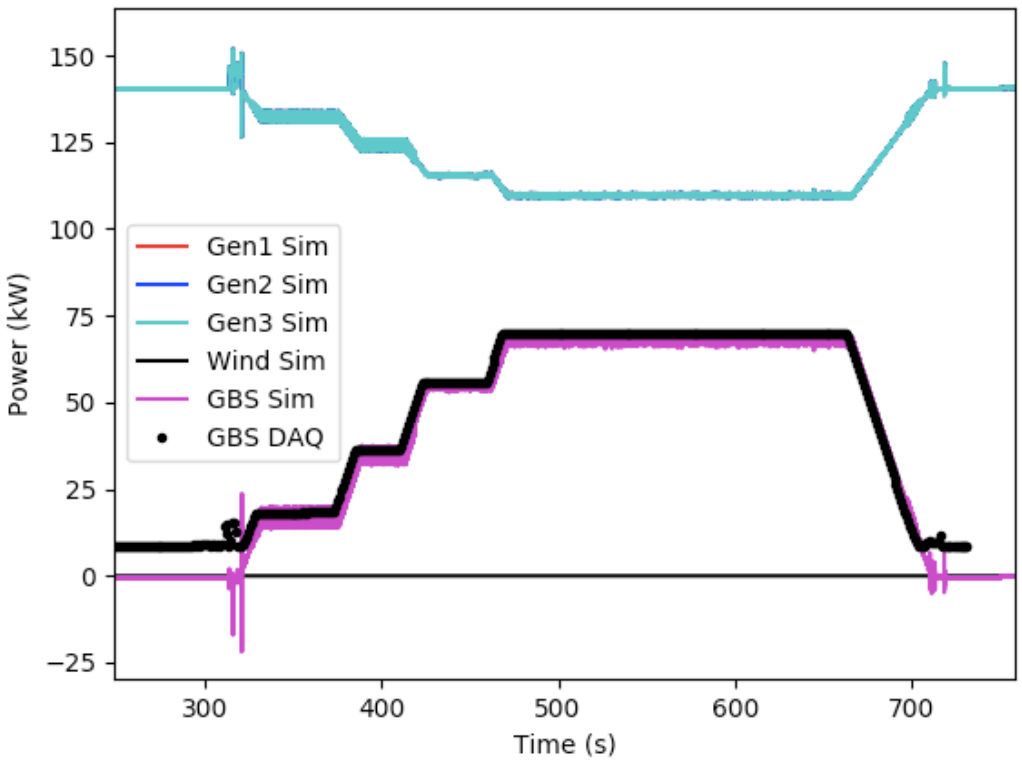
- Simulated Two 1.5 kW virtual loads operated in stairstep pattern
  - Replicated by GFM connected to physical load bank
- Curves show method is stable under abrupt load changes,
- Accuracy between the three measurements is within 5 percent of error

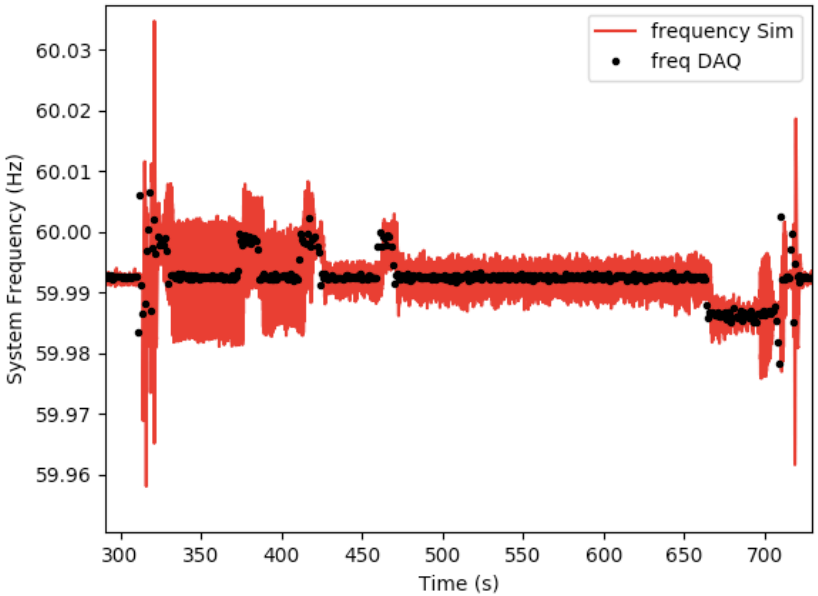


- Small amount of reactive powers is present due to the reactance of output LC filter
- Successfully done with multiple types of GFM with and without transformers
- Method and results being presented at Photovoltaic Specialists Conference June 15-19.

Power Hardware in Loop of GFM in St. Mary's

- Implemented PHIL GFM into St. Mary's System
  - GFM (ABB PCS100, 100 kW) powered by NHR Battery Emulator connected to Ametek grid simulator
  - GFM replicated in simulation as three single-phase current sources controlled by measured current in laboratory
  - Operated GFM in PQ mode with commanded power of 0.2, 0.4, 0.5, and 0.75 p.u.
    - Simulated generators decrease in power as GBS power increases (droop controlled)
    - Laboratory DAQ data (black) agrees with simulation





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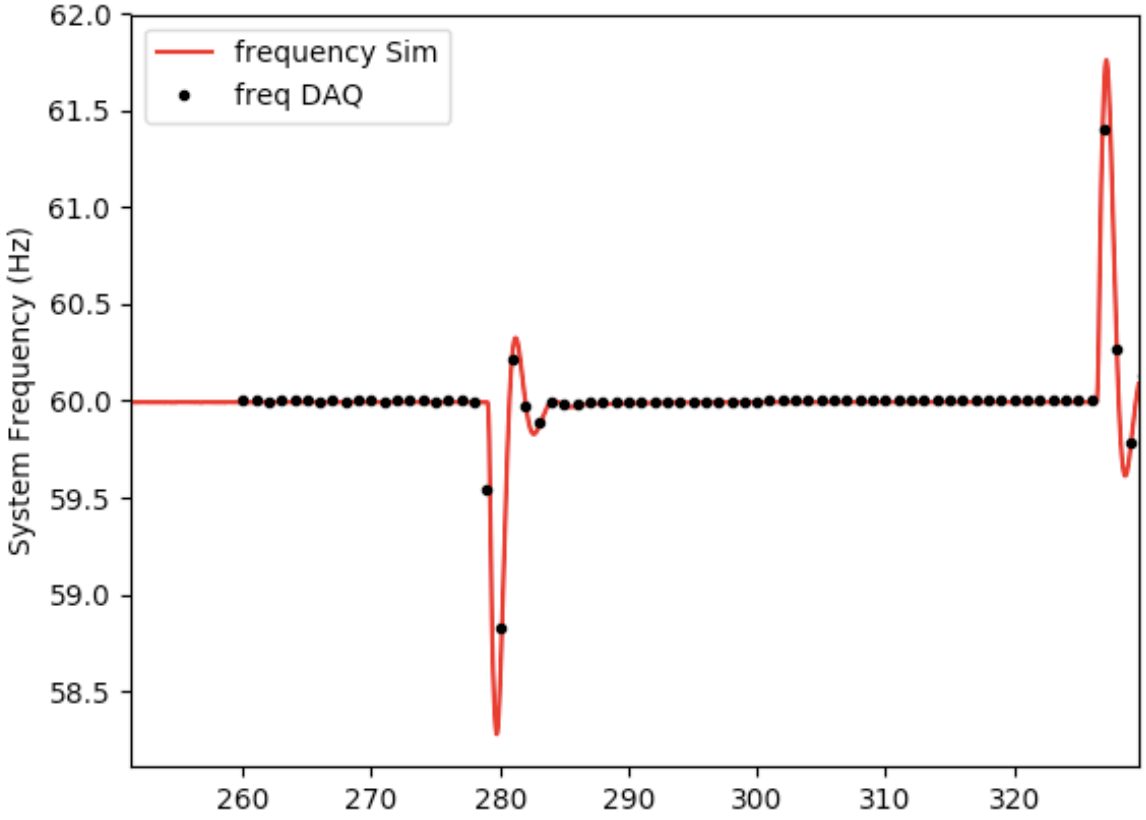
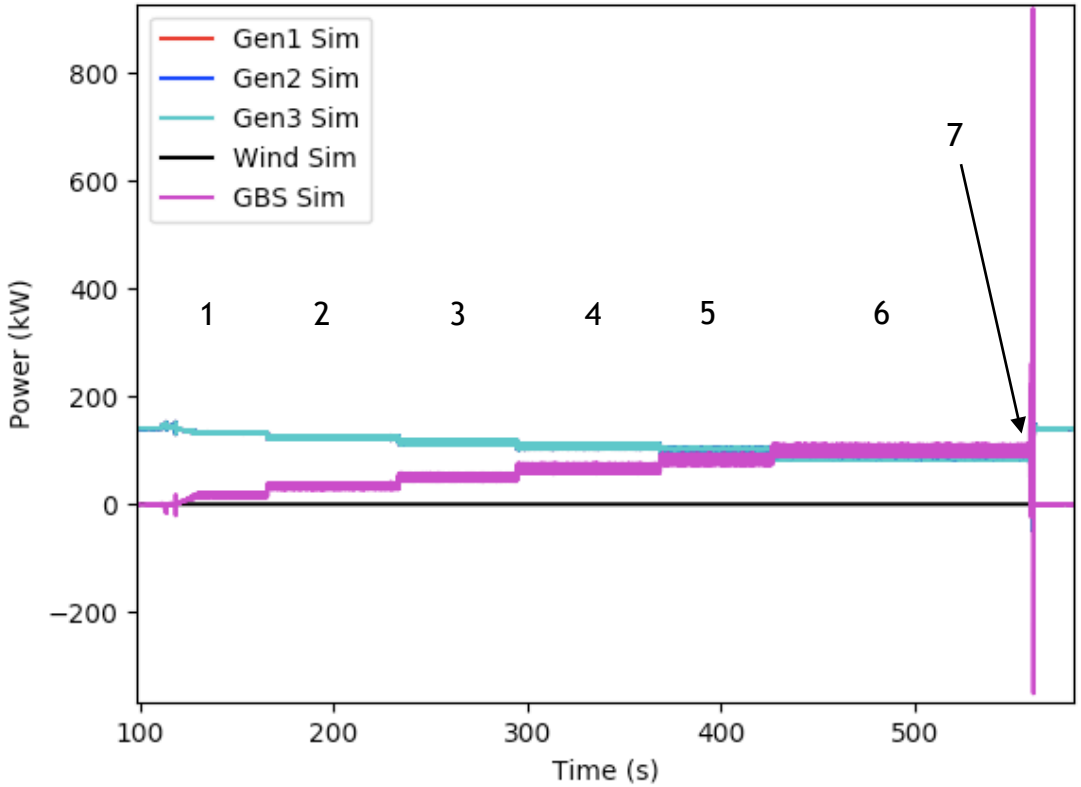


- Accurately replicates spinning reserve in loss-of wind scenario
- Power injection (100 kW) small compared to proposed system to be installed at St. Mary's (1 MW)
- Need to simulate higher power than is possible in laboratory
  - Typically done by adding proportionality constant to current injection
  - Emulates larger GBS

Power Hardware in Loop of GFM in St. Mary's

- Implemented PHIL GFM into St. Mary's System
  - GFM (ABB PCS100, 100 kW) powered by NHR Battery Emulator connected to Ametek grid simulator
  - PCS100 provides 20 kW real power
    - Adjust proportionality constant from 1 to 13
    - At constant of 7, high frequency noise causes instability
      - Trips grid simulator and GFM



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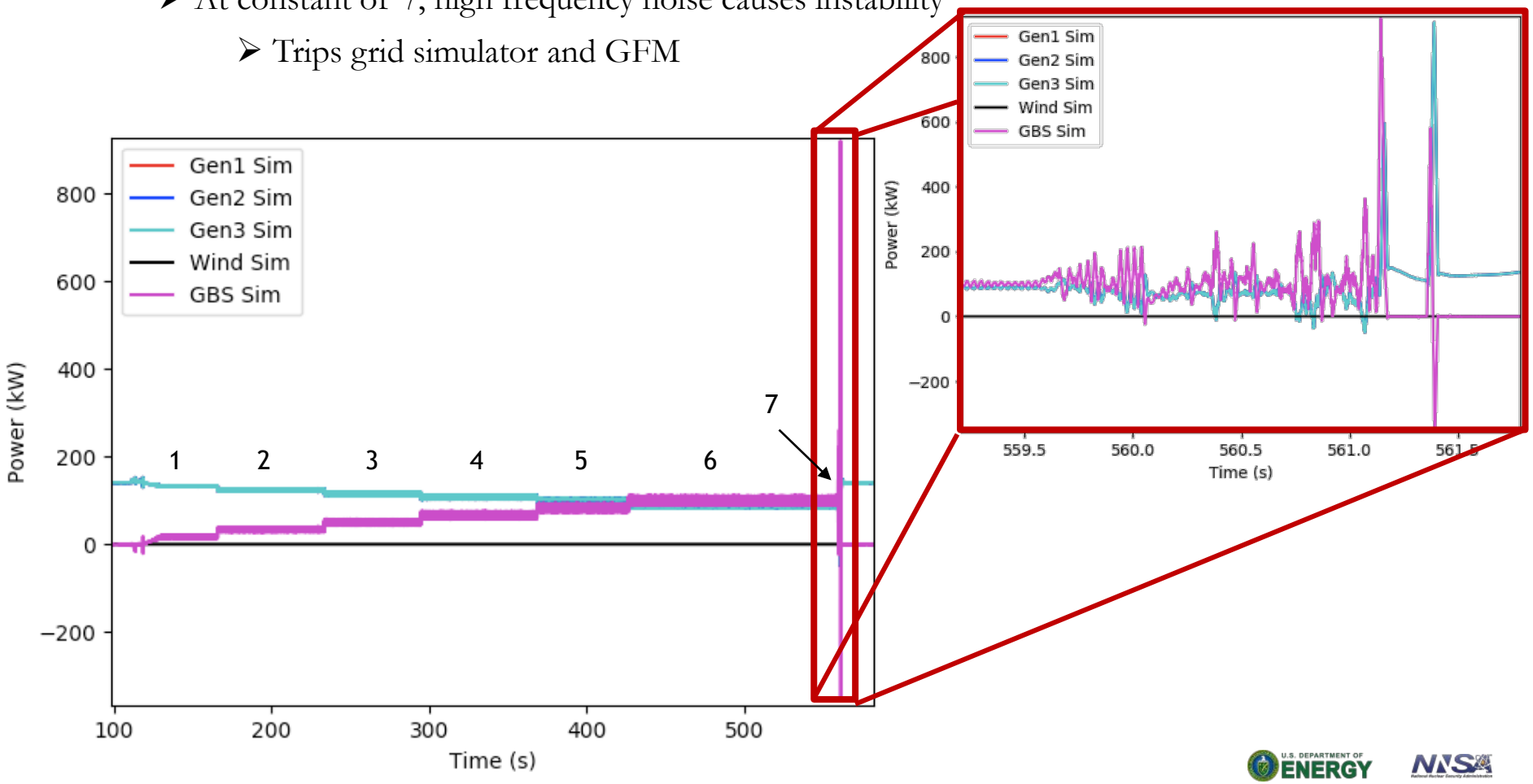
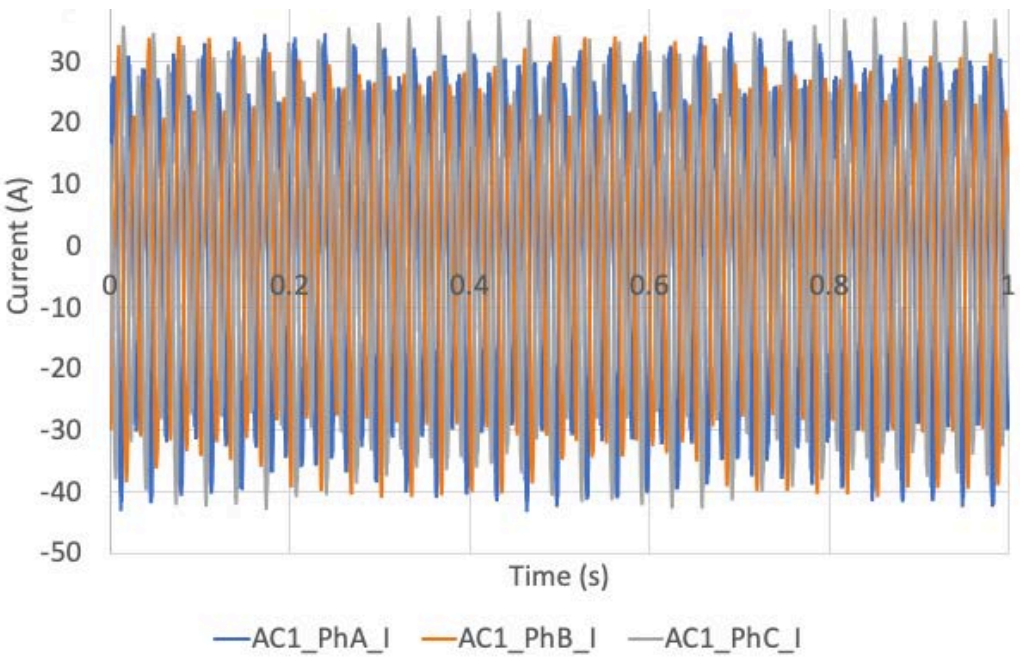


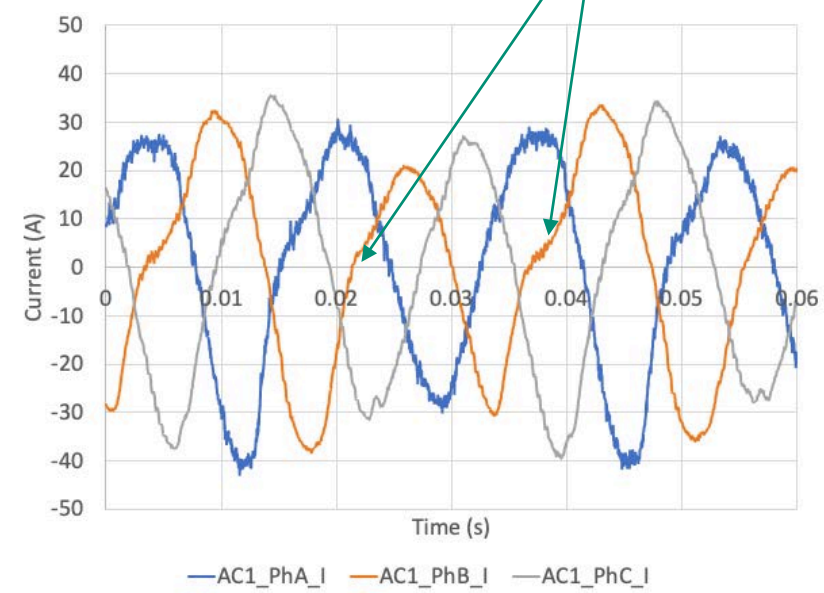
Power Hardware in Loop of GFM in St. Mary's

- Currently working to track down nature of instability
  - Same GFM/gain concept used successfully in larger grids (Cordova, AK ~1MW)
  - Believe problem is exacerbated by small size of system (low inertia)

- Currently evaluating other GFM (~15-30 kW) to determine if problem is universal
- Investigation of physical current at GFM indicates large magnetization current
  - Magnetization current being multiplied as well
  - Injection of distorted waveforms may introduce instability in small system
  - Investigating ways to smooth or cancel out magnetization current

Highly distorted waveform due to magnetization current



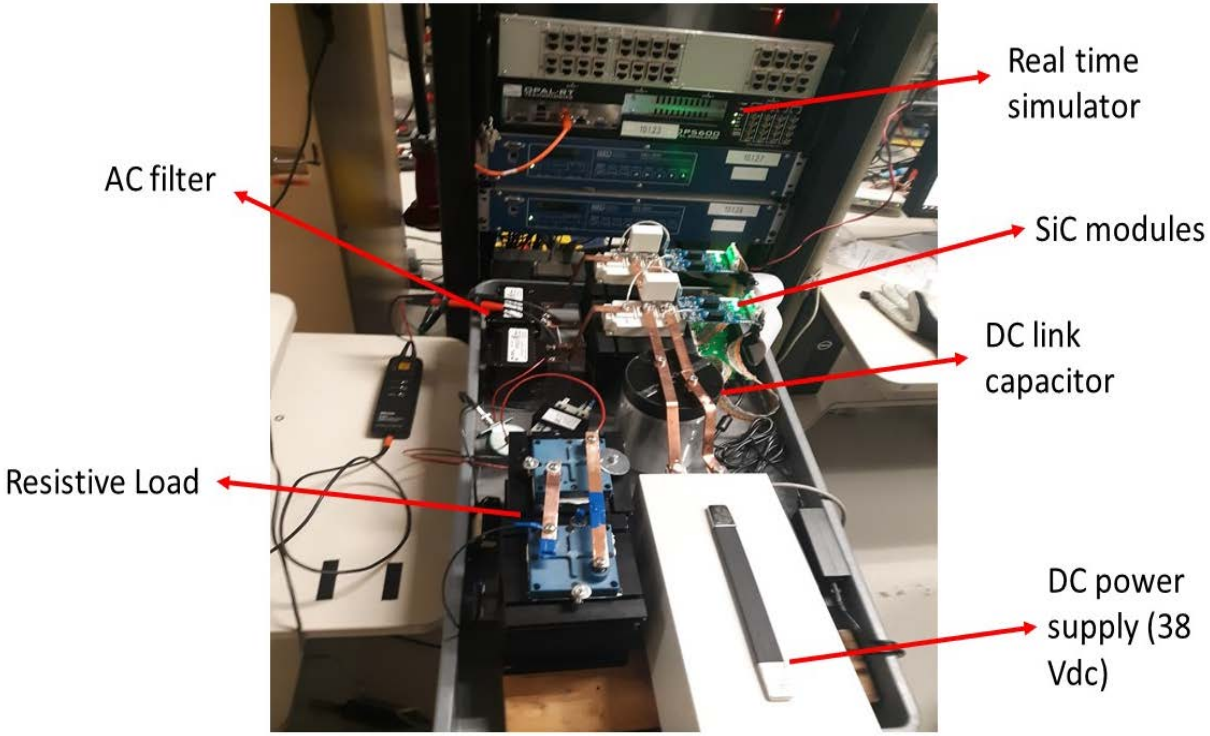


GFM Testbed to evaluate control schemes

- PHIL evaluation of commercial hardware is valuable, but does not allow us to compare control schemes
  - High accuracy → get real behavior of device that could be installed
  - Limited flexibility → no control over control architecture, limited ability input into behavior
    - In some cases can only alter setpoints or ramp rates
    - No ability to change controls internal to device

- Need hardware testbed for GFM that has complete flexibility for changing/adapting control schemes
  - Not just parameters in a particular mode
  - Comparing different control modes with similar hardware
  - Accuracy of real hardware with flexibility of simulation

- Developing GFM hardware testbed that has flexible controls
  - System that is highly flexible while still accurate

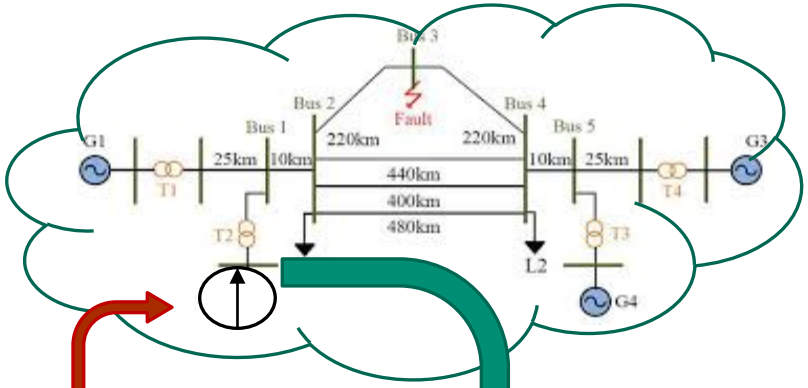


GFM Testbed to evaluate control schemes

- Utilizing Opal RT system to supply gate drive signals to hardware in addition to power system simulation
  - Time Stamped Digital Outputs allow for ~300kHz switching within 40 μs timestep
  - PWM changes are possible within simulation timestep
  - Simulink models for various control schemes
    - Extremely flexible

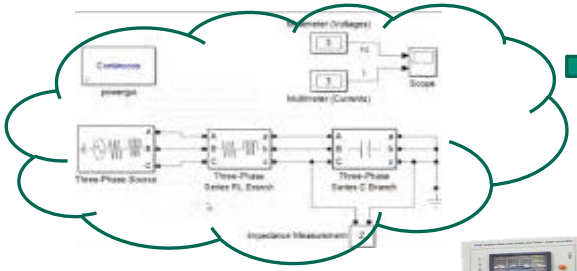
Opal RT

Power System Simulation



Current injected

AC Voltage



PWM Signals

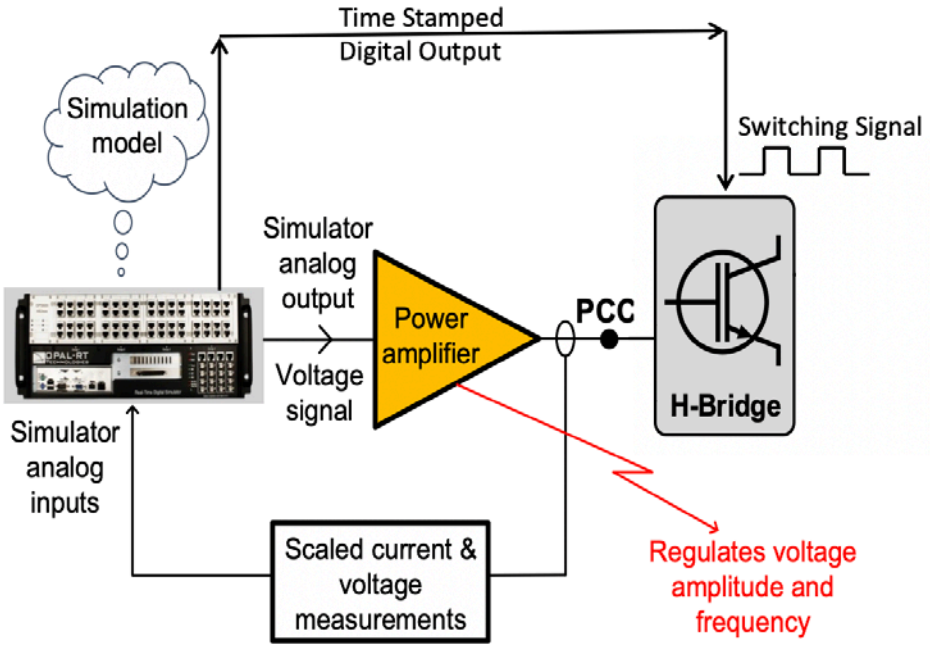
Digital twin at node A

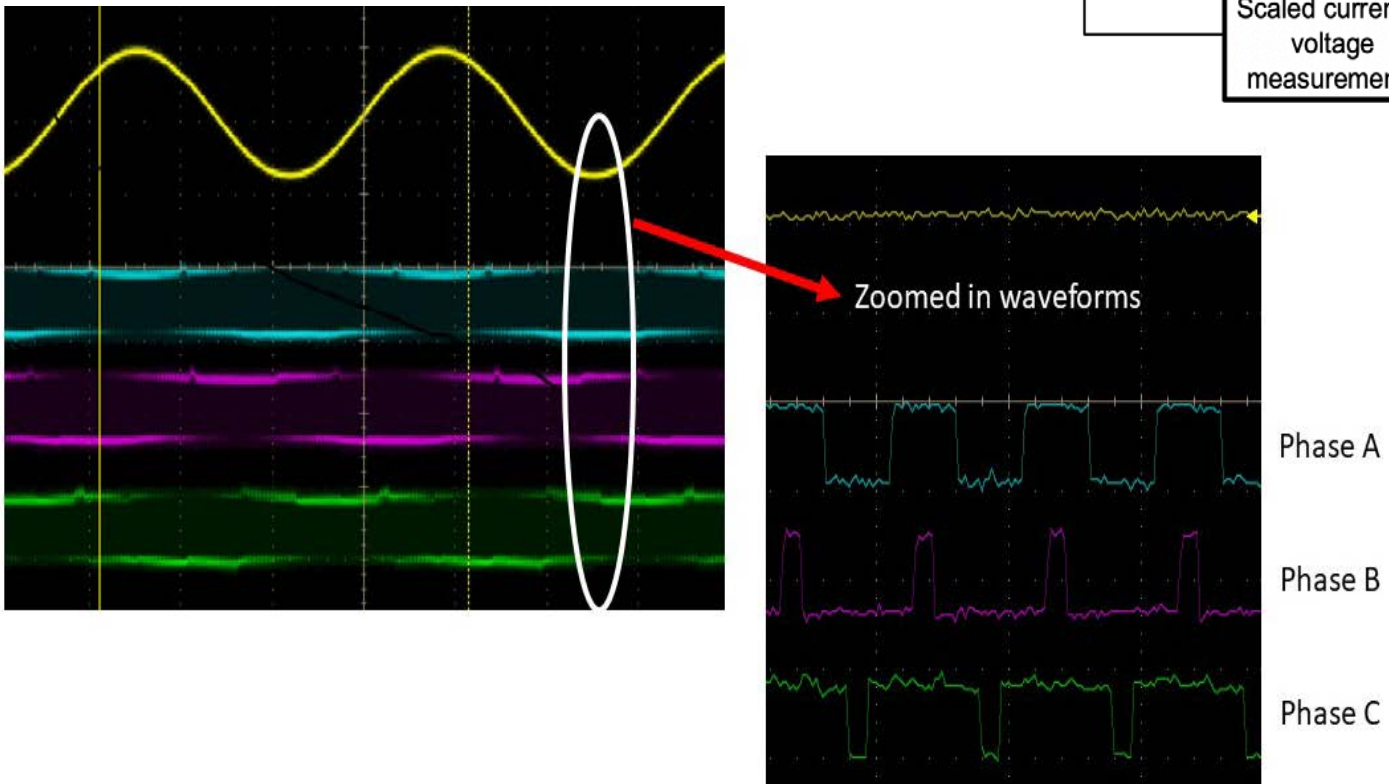
GFM Testbed

AC Amplifier

GFM Testbed to evaluate control schemes

- Preliminary testing has focused on 1ϕ, low voltage version
  - Demonstrate ability to control hardware via time stamped digital outputs
  - Demonstrate stable control scheme and ability to implement in simulation



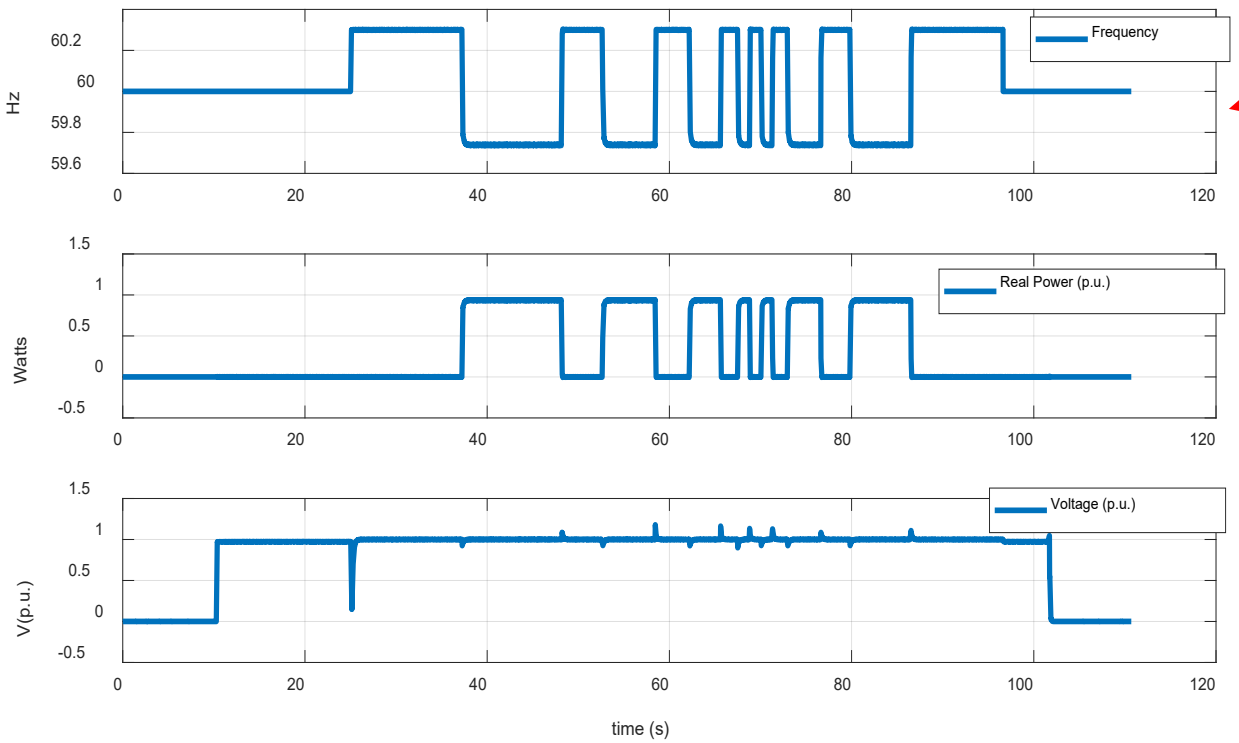


GFM Testbed to evaluate control schemes

- Evaluated closed loop simulation of GFM testbed
  - Behavior under variable load
  - Frequency behavior follows power demand due to droop curve
  - Constant output voltage is maintained

- Current work focuses on increasing power 7 kW (10 A)
  - Working on sizing of components and developing heatsink capabilities
  - Layout of PCB boards for higher power version

S_{base}	60 VA
V_{base}	23 V
P-f droop	1 %
Q-V droop	5 %



Frequency jumps according to real power demands

Power demand toggles from 0 to 1 p.u.

Regardless of power demands, the voltage is maintained at 1 p.u.

Summary

- GFM for spinning reserve has been shown to improve power quality in the St. Mary's system

- Successfully implemented GFM in PHIL for the St. Mary's model
  - Evaluated PQ, V-f, and loss-of-wind scenario
  - Increasing power level yielding system instability
    - Identified cause as magnetization current in the physical setup

- Fabricated and demonstrated a flexible testbed for GFM under low power
  - Demonstrated ability to switch up to 300 kHz
  - Implemented droop control scheme in testbed
    - Stability to step load changes in simulation at 50 kHz

Tech Transfer

Publications:

1. J. Hernandez-Alvidrez, A. Summers, M. J. Reno, J. Flicker, and N. Pragallapati, "Simulation of Grid-Forming Inverters Dynamic Models using a Power Hardware-in-the-Loop Testbed," in *IEEE Photovoltaic Specialists Conference (PVSC)*, 2019.
2. J. Hernandez-Alvidrez, N. Gurule, M. J. Reno, J. Flicker, A. Summers, and A. Ellis, ”Method to Interface Grid-Forming Inverters into Power Hardware in the Loop Setups," in *IEEE Photovoltaic Specialists Conference (PVSC)*, 2020. (Accepted)
3. J. Flicker, J. Hernandez-Alvidrez, M. Shirazi, J. Vandermeer, W. Thomson, ”Grid Forming Inverters Spinning Reserve in Hybrid Diesel Microgrids," in *IEEE Power and Energy Society General Meeting (PESGM)*, 2020 (Accepted).
4. J. Hernandez-Alvidrez, J. Flicker, M. Shirazi, J. Vandermeer, W. Thomson, ”Grid Forming Inverter Control in Hybrid Diesel Microgrids,” *Energies*, 2020 (Submitted).

Collaborators:

1. Robert Lasseter, University of Wisconsin Madison, Grid forming inverter modeling
2. Venkat Banunarayanan, National Rural Energy Cooperative Association, Grid forming inverters for rural resilience
3. Mariko Shirazi, Jeremy Vandermeer, Alaska Center for Energy and Power, University of Alaska-Fairbanks. Model validation and acceptance testing
4. William Thomson, Bill Stamm, Alaska Village Electric Cooperative. System Modeling

Future Work

Milestone Description	Schedule
AOP Milestone 1. Demonstrate GFM Hardware-in-Loop in St Mary's model	06/30/2020
AOP Milestone 2. Identify screening criteria for GBS in rural communities	07/30/2020
AOP Milestone 3. GBS Model Validation using PMU and acceptance testing	09/30/2020
AOP Milestone 4. DCEI Extension of model	09/30/2020

- GFM PHIL
  - Increase power level of GFM in simulation
    - Evaluating stability in gain of other (smaller) GFM
    - Working on separating out magnetization current component from simulation to ensure stability under high power conditions

- GFM Testbed
  - Fabricating higher power (7 kW) version of testbed
  - Extension to 3ϕ system

Future Work

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- Installation of GBS in St. Mary's and model validation
  - Contracts with AVEC and ACEP are in place
  - Worked with AVEC/ACEP to evaluate candidate GBS systems for St. Mary's
  - Procurement of 1 MW unit underway → ACEP acceptance testing before install
    - Possible delivery delays due to COVID situation in US/Canada
  - Working with ACEP to develop laboratory acceptance plan for unit
    - Testing results will be used to validate simulation models of GFM
- Extension of models/lessons learned from islanded to rural and other systems
  - Currently working with National Electric Cooperative Association (NRECA) to identify specific power quality issues on member distribution systems
    - Narrow issues to those that can be mitigated with GFM incorporation
  - Identifying cooperatives interested in participating in modeling activities to quantify benefits of GFM on their system
    - Utilities have been struggling with COVID response

Questions

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