GFM Inverter Interoperability Through Hardware Testing

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UNIFI 1-MW Demo Objective

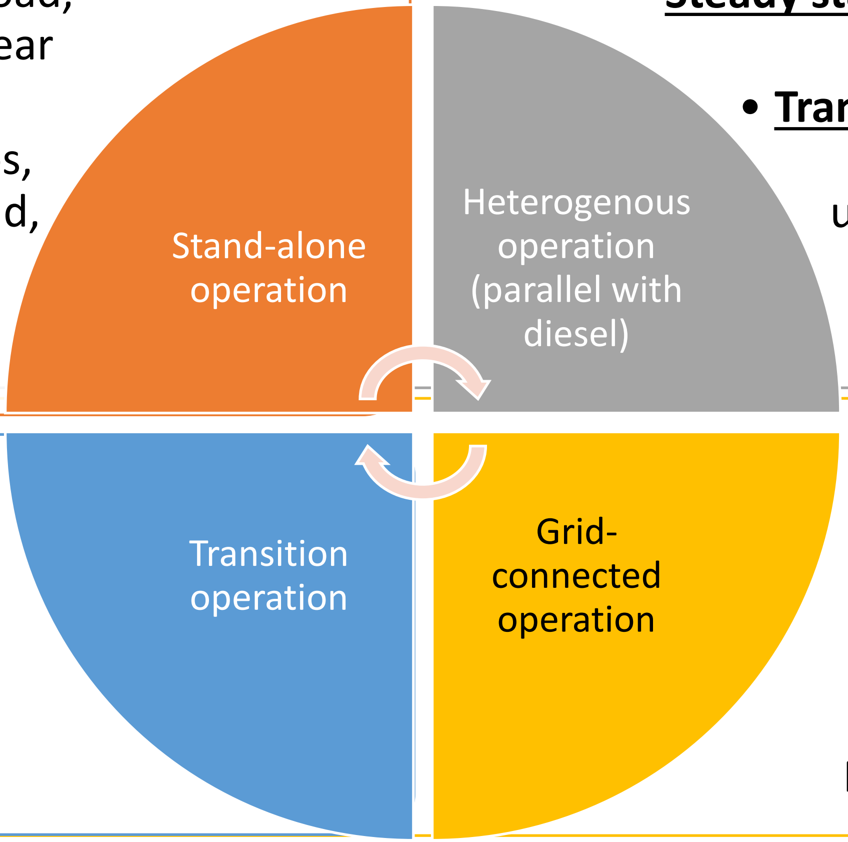
- There is a lack of standard testing protocols for grid-forming (GFM) inverters.
  - Develop standard testing protocols to understand the performance of GFM inverters.
- Explore the interoperability and functionalities of GFM inverters.
  - Test the key operation functions and modes of GFM inverters.
  - Use findings to drive GFM specifications.
- Provide findings and guidelines for industry and academia.
  - Utility: How to configure and control GFM inverters?
  - Vendor: What are the specs of GFM inverters?
  - Academia: What are the research gaps and key challenges?

Goal: Illustrate the interoperability guidelines at work with multiple vendors.

High-Level View of the Test Plan

- **<u>Steady state</u>**: Balanced load, unbalanced load, nonlinear load, sinking power
- **<u>Transient test</u>**: Load steps, inductive inrush, overload, DC dynamics, secondary control

- **<u>Steady state</u>**: Balanced load and sinking power
- **<u>Transient state</u>**: Load step, loss of generation, unequal power sharing, secondary control



- Synchronization operation
- Islanding operation

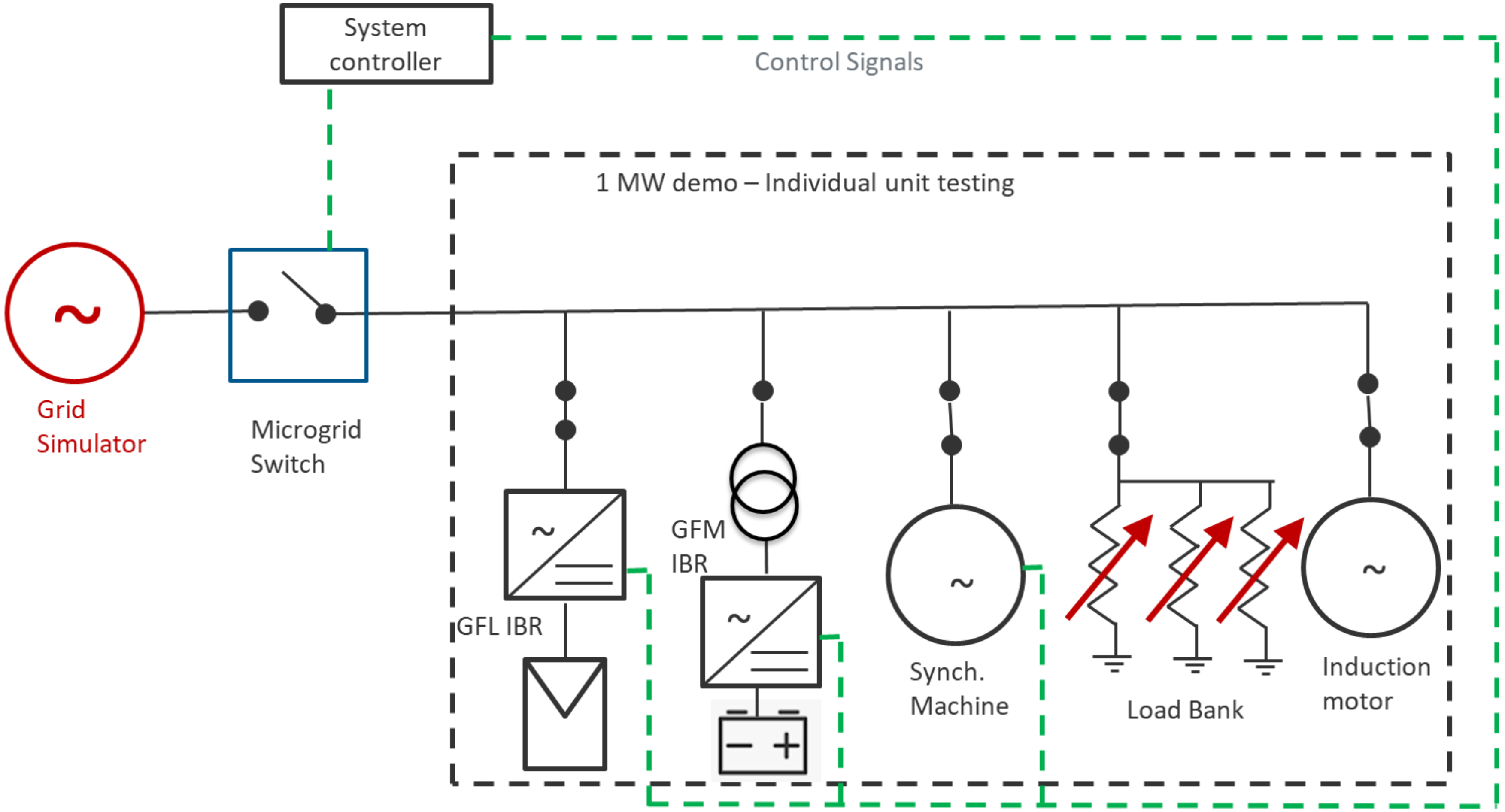
- **<u>Steady state</u>**: Sourcing power, sinking power
- **<u>Transient state</u>**: Freq. and voltage steps

- <u>Steady state</u>: 5%, 10%, 25%, 50%, 75%, 100%, PF=1, 0.8 lagging and leading, pure inductive and capacitive loads
- <u>Transient state</u>: 25%, 50%, 75% and 100% PF=1, 0.8 lagging and leading
- <u>Transition operation</u>: 50% PF=1, 0.8 lagging and leading

Inverter Specifications

Specification	GFM#1	GFM#2	GFM#3	GFM#4	GFM#5
Frequency droop settings	0.25%	0.1 Hz gives 7.8 kW at 500	0.5 Hz	50, GFM droop W/P proportional Gain (Hz/W)	n/a (no droop, isochronous mode is configured and cannot change it)
Frequency droop	0.25%	0.67%	0.83%	0.83% (actually 0.35%)	
Voltage droop settings	5%	10 V gives 7.22 kVAR for 2160	24 V	2500, GFM droop V/Q proportional Gain (Vrms/Var)	
Voltage droop	5%	6.48%	5%	6.8%	
Synch check	Yes (GCB and MCB)	No	Yes (GCB)	Yes (GCB)	Yes (GCB)
Secondary control	Yes	Yes	Yes	Yes	No
Operation mode	GFM, GFL, and grid-supporting control	GFL and GFM control	GFL and GFM control	GFM, GFL, and grid-supporting control	Only GFM control
Communication protocol	Modbus TCP/IP			Modbus RS485	HTTP (REST command)

Testing Circuit

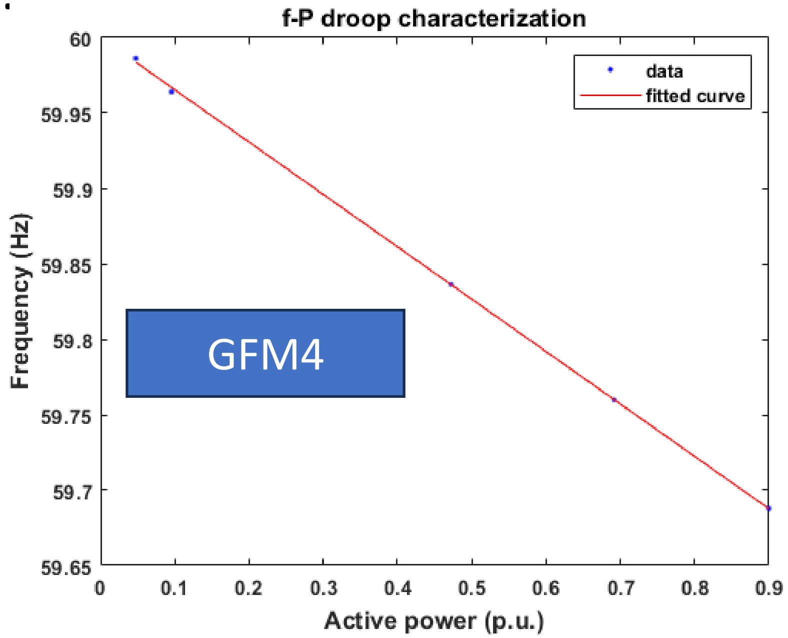


- The same testing circuit for easy configuration and testing
- The same testing protocol for fair comparison:
    - Power quality
    - Overloading capability
    - Transient stability.
- A system controller to dispatch all the elements

Characterization of Droop (f-p)

- Testing conditions
  - PF1 load with 5%, 10%, 25%, 50%, 75%, and 100% loading of the capacity of the GFM inverter.
  - Record the frequency and active power (p.u.).
  - Plot the relationship between the active power (x-axis) and the frequency (y-axis)
  - Characterize the relationship mathematically with a fitting function.

- Testing results
  - GFM inverters 1, 2, and 3 have the correct droop characterization as the setting value.
  - GFM 4 has a misaligned droop characterization compared to the setting values.
    - The experimentally characterized droop is smaller than the setting value.
    - Find the linear relationship between the actual droop parameters and the default setting (**resolve the problem!**).

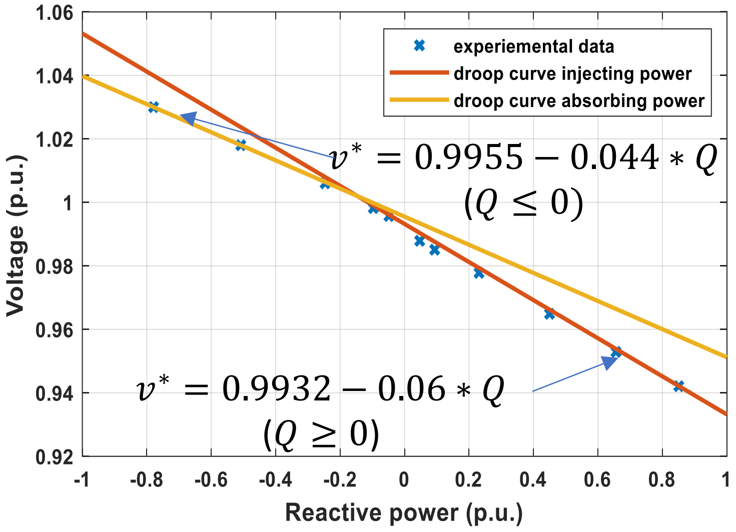


$$f^* = 60 - 0.2054 * P \left(m = \frac{0.2054}{60} = 0.35\% \right)$$

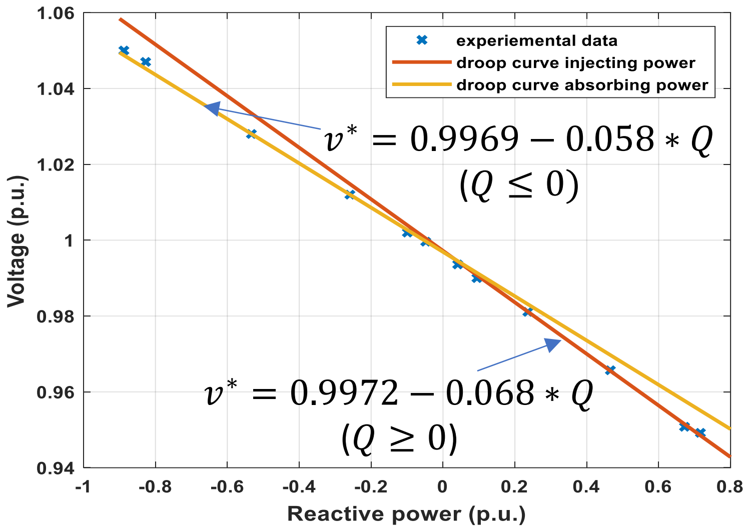
Default is 0.83%.

Characterization of Droop (v-q)

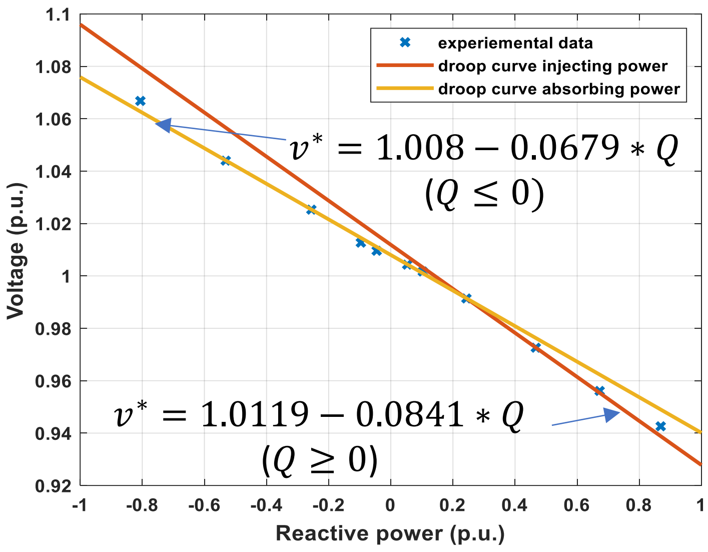
GFM 1 voltage droop characterization



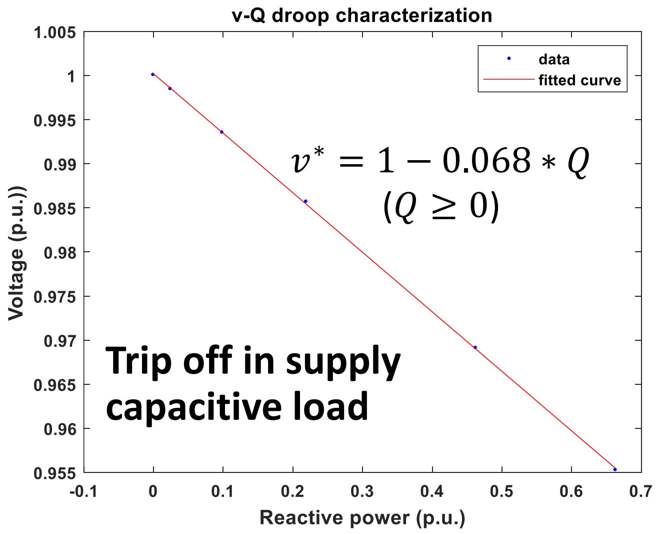
GFM 2 voltage droop characterization



GFM 3 voltage droop characterization



GFM 4 voltage droop characterization



Learnings and findings:

- Not all GFM inverters have voltage droop coefficients that are the same as the defined value.
  - There are different droop characteristics in injecting and absorbing Q:
    - Injecting reactive power: The intercept is lower than “1” p.u., and the droop slope is higher than the defined value.
    - Absorbing reactive power: The intercept is lower than “1” p.u., and the droop slope is lower than the defined value.

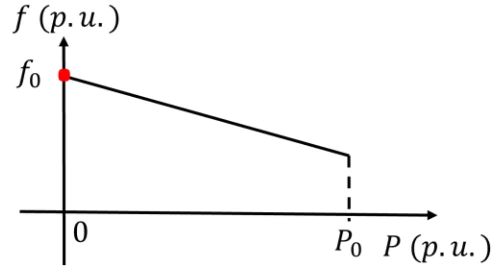
Black Start

Inverter	Results description	Pass/fail
GFM#1	• The inverter dose not have a soft black start. The voltage has a peak of 1.4 p.u., and reach steady state after 0.15 seconds • For 50% and 100% load connection, the inverter reaches steady state within less than 2 cycles	Pass
GFM#2	• The inverter has a soft black start. The voltage reaches steady state after less than 0.1 seconds • For 50% and 100% load connection, the inverter reaches steady state within less than 2 cycles	Pass
GFM#3	• The inverter has a soft black start. The voltage reaches steady state after 4.88 seconds • For 50% and 100% load connection, the inverter reaches steady state within less than 2 cycles	Pass
GFM#4	• The inverter has a soft black start. The voltage reaches steady state after 0.1 seconds • For 50% and 100% load connection, the inverter reaches steady state within less than 2 cycles	Pass
GFM#5	• The inverter has a soft black start. The voltage reaches steady state after 0.1 seconds • For 50% and 100% load connection, the inverter reaches steady state within less than 2 cycles	Pass

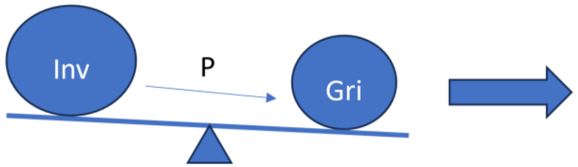
Dispatching GFM Inverters

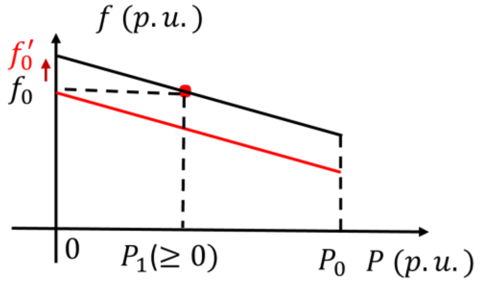
Grid-Connected Operation

Scenario #1: both are 60 Hz, no power flow

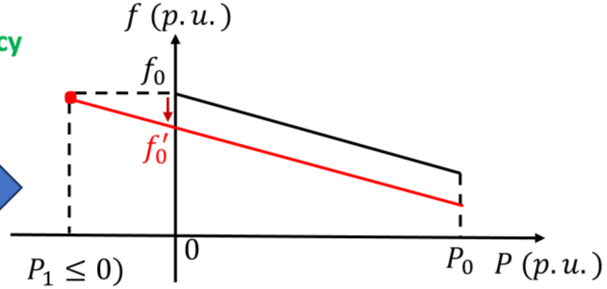


Scenario #2: inverter shifts up the frequency droop intercept, active power flows from the inverter to the grid side.





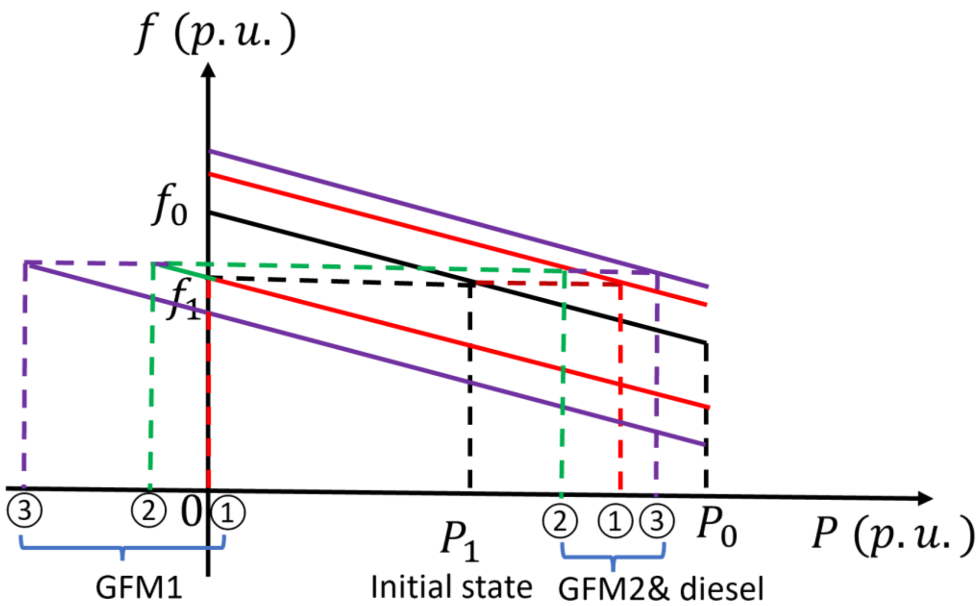
Scenario #3: inverter shifts down the frequency droop intercept, active power flows from the grid side to the inverter.



Inv: inverter; Gri: grid

$$f^* = 60 + \Delta f = 60 + m * P * 60$$

Islanded Operation



Start with equal power sharing:

① GFM 1 goes to zero power.

② Bring in grid-following (GFL).

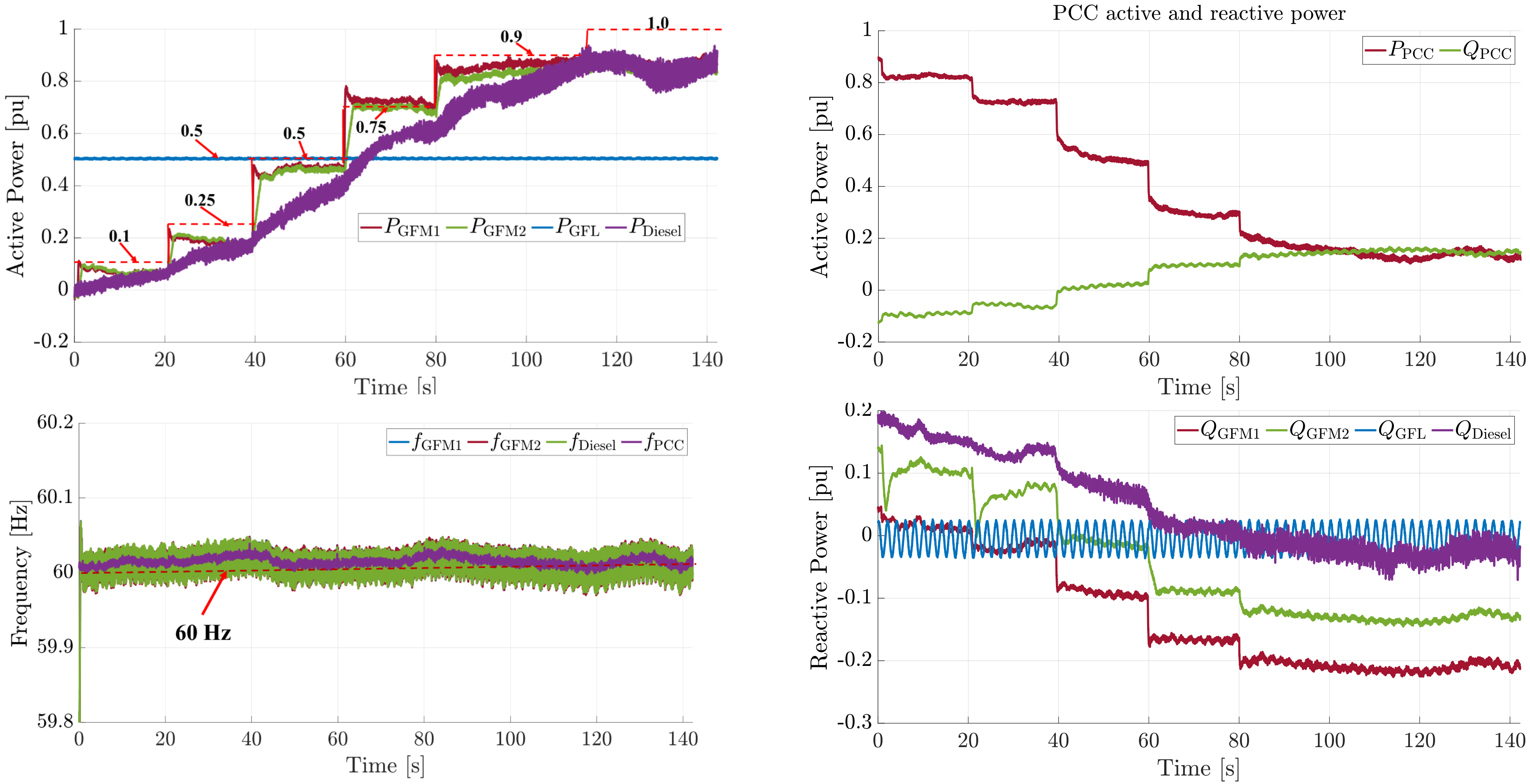
③ Charge GFM 1.

$$\Delta f = (P_{new} - P_{old}) * m * 60$$

Dispatching GFM Inverters—Grid-Connected Mode

Testing conditions and procedures:

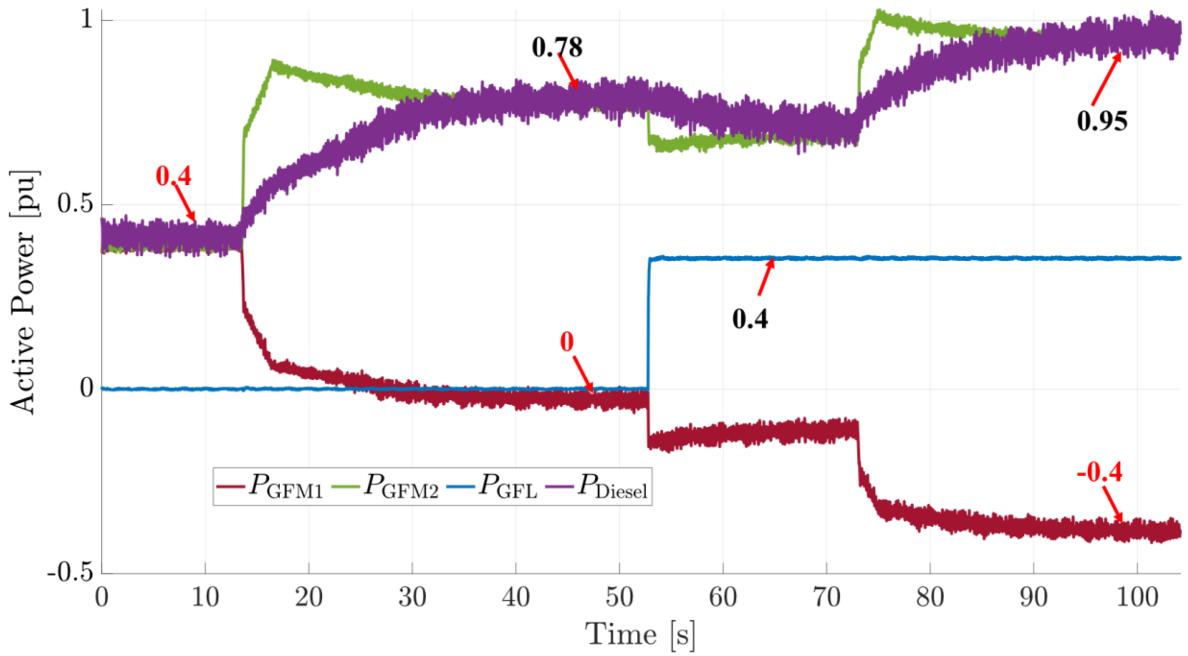
- The utility grid is used instead of the grid simulator, PF1 load and GFL with 50% dispatch.
- Dispatch each GFM source to the target power (5%, 10%, 25%, 50%, 75%, and 100%).

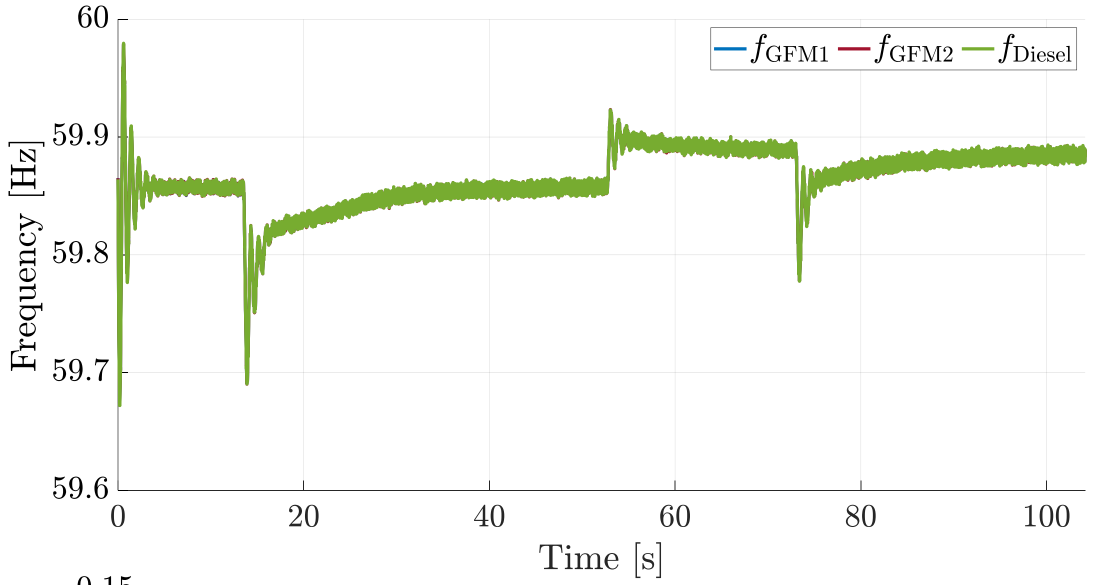


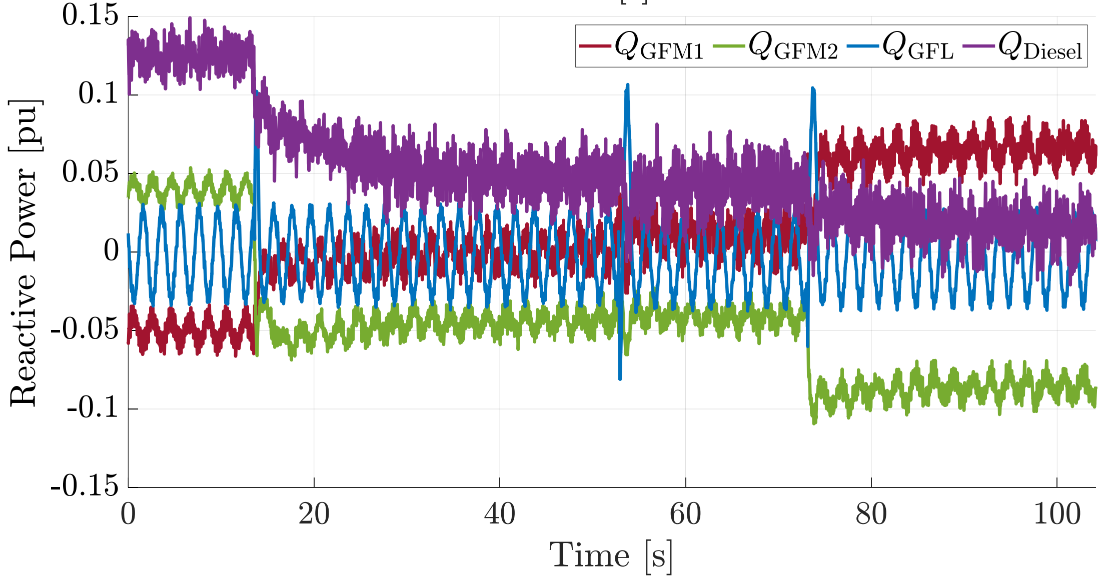
Dispatching GFM Inverters—Islanded Mode

Testing procedures:

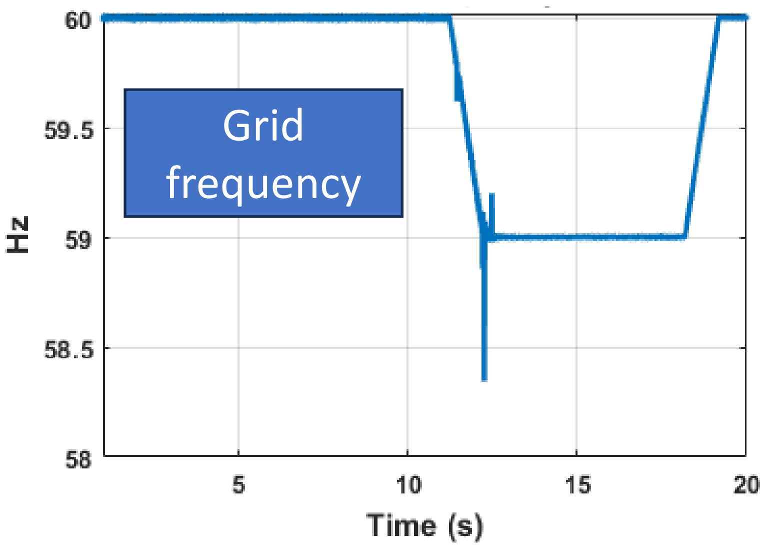
- Objective: Start from equal power sharing to charge GFM 1 with 40% power.
- Strategy: ① Let the GFM output zero active power by dispatching GFM 2 and diesel; ② bring in GFL; ③ dispatch GFM 2 and diesel to let GFM 1 charge to 40% power.

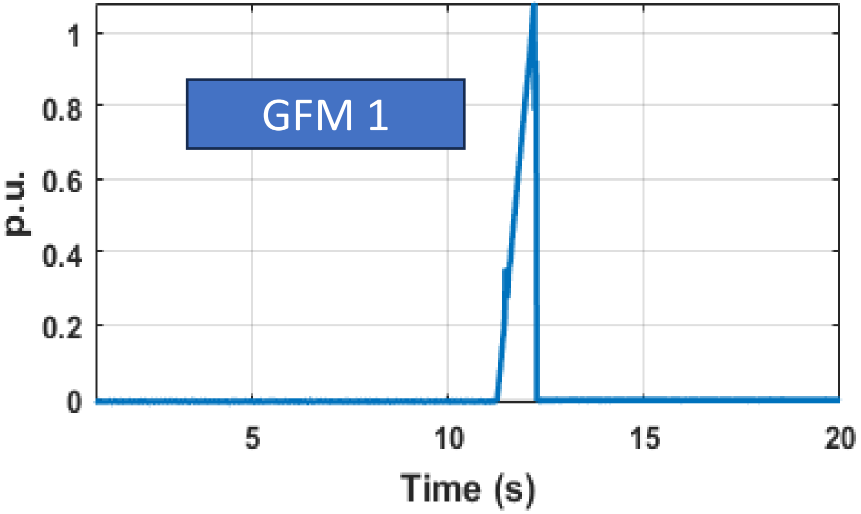


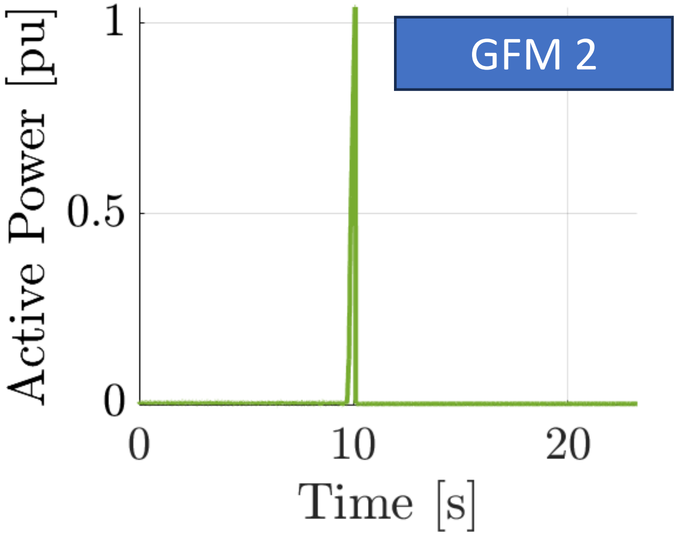


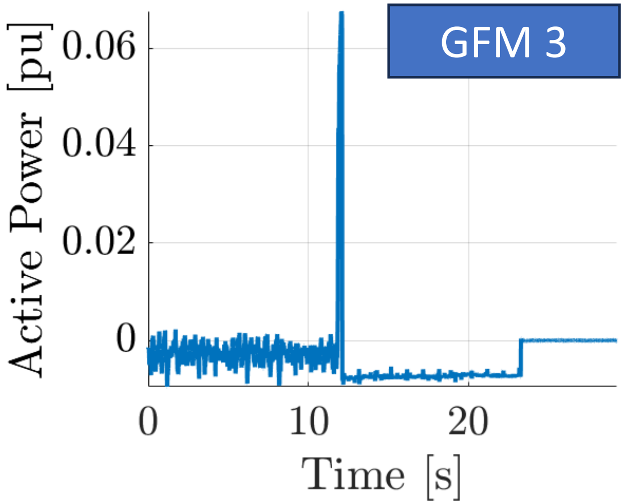


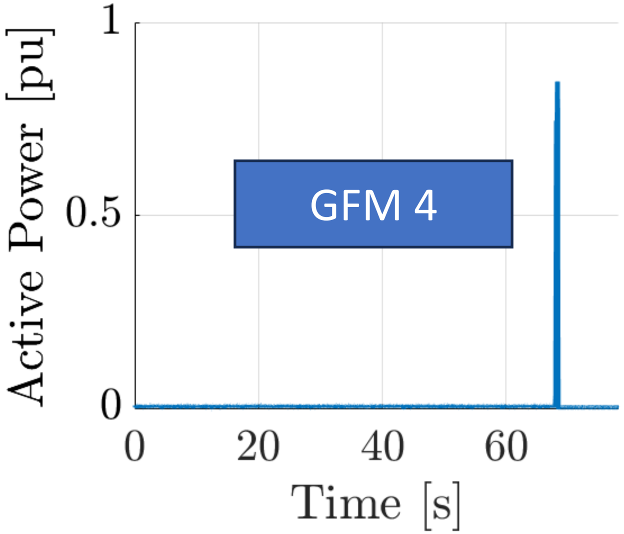
Rate of Change of Frequency (ROCOF) Test

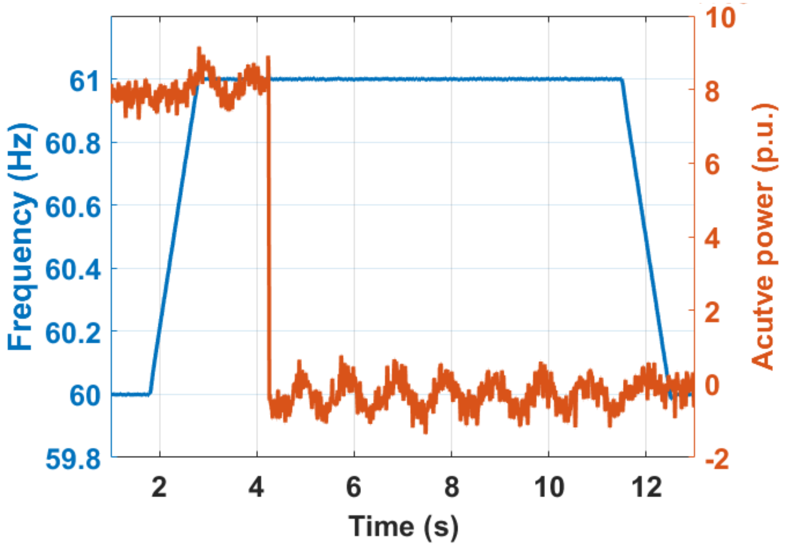






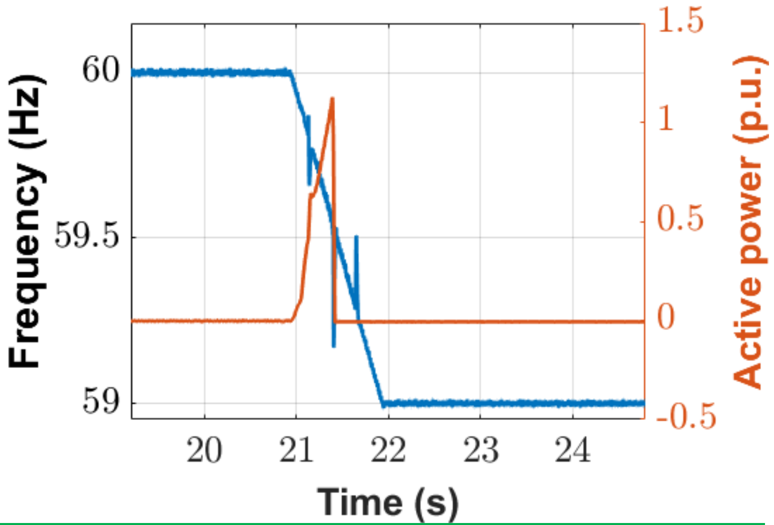




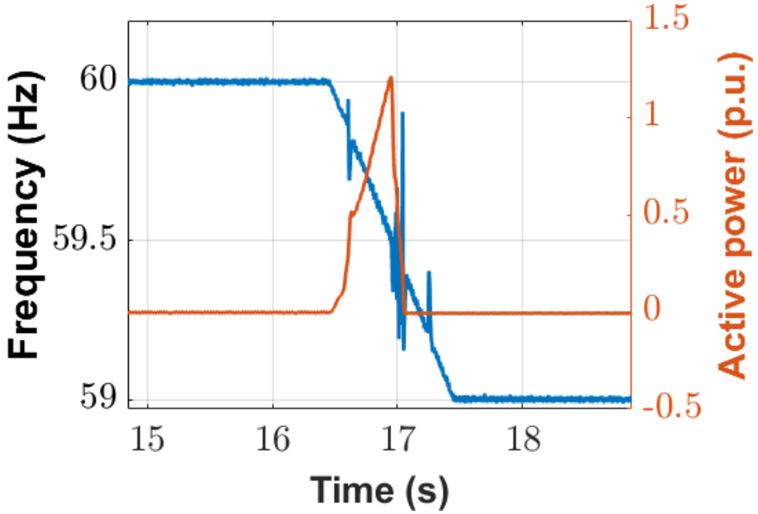


Troubleshooting for GFM 2

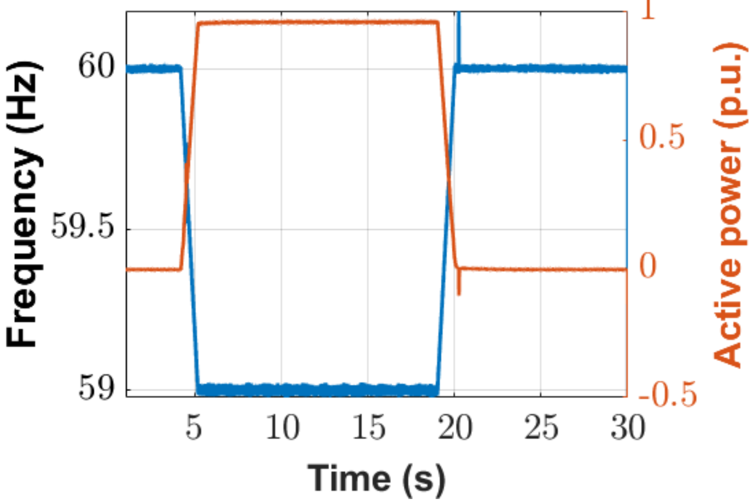
0.6% droop with 1.2-p.u. DC current



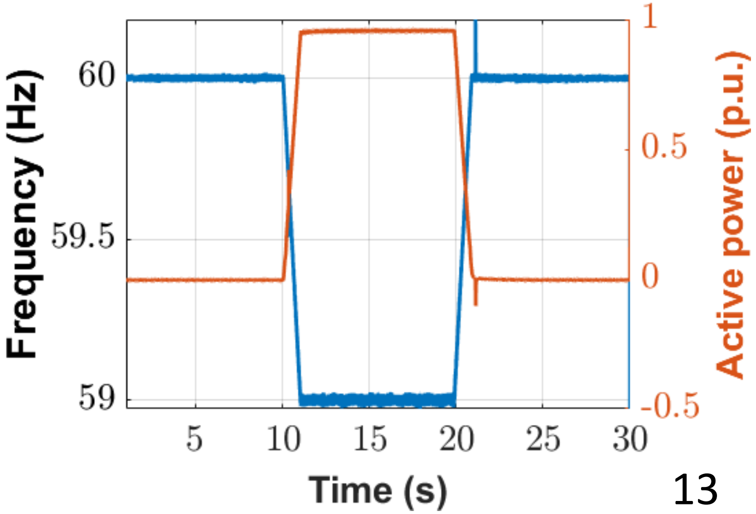
0.6% droop with 1.5-p.u. DC current



1.67% droop with 1.5-p.u. DC current



1.67% droop with 1.2-p.u. DC current

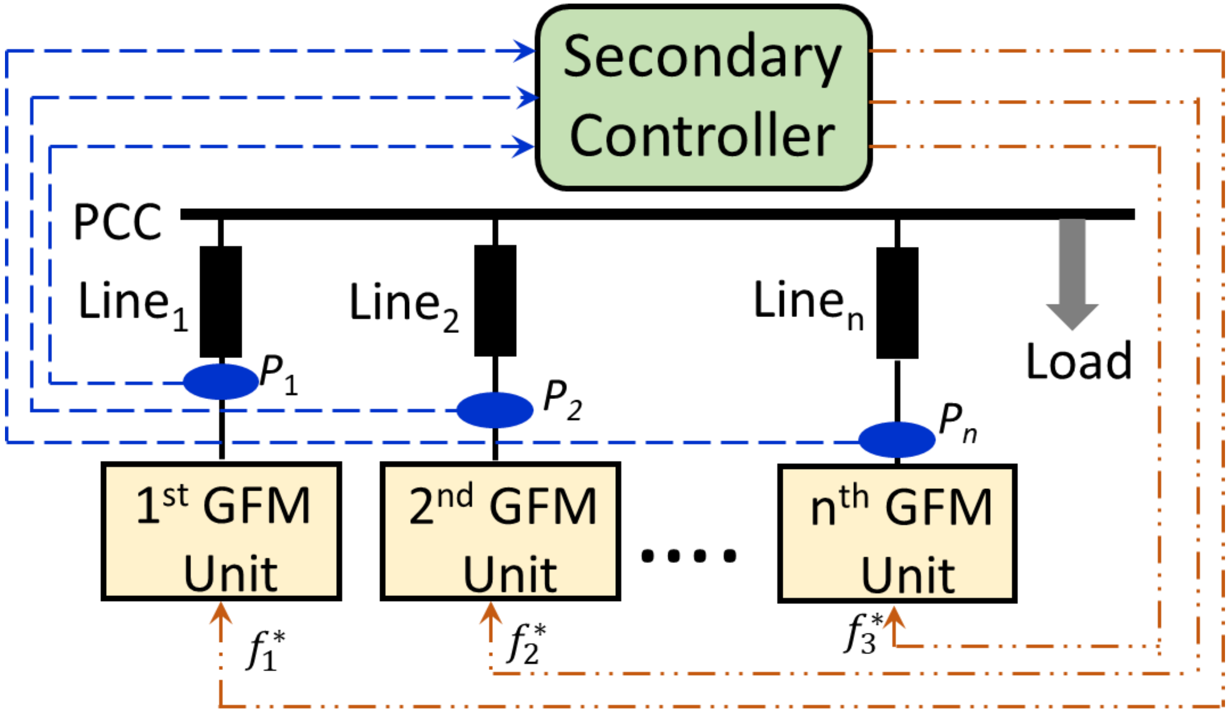


The DC side matters a lot! Cannot simply say that the inverter passed/ failed the ROCOF test. The DC side capacity is important!

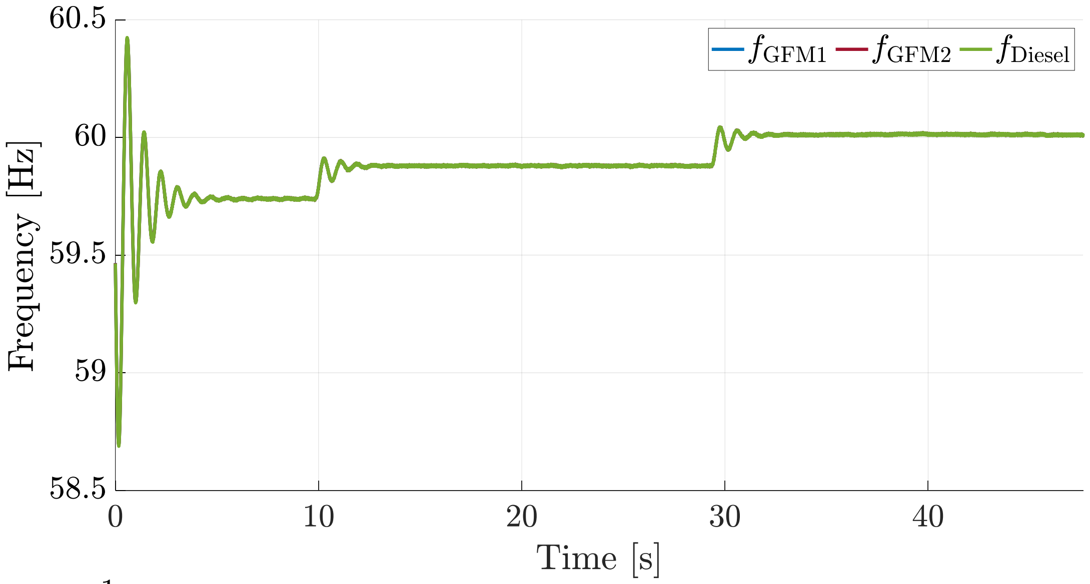
$$H = \frac{\Delta P \cdot f_0}{2S_{rating} \cdot 1\ Hz/s}$$

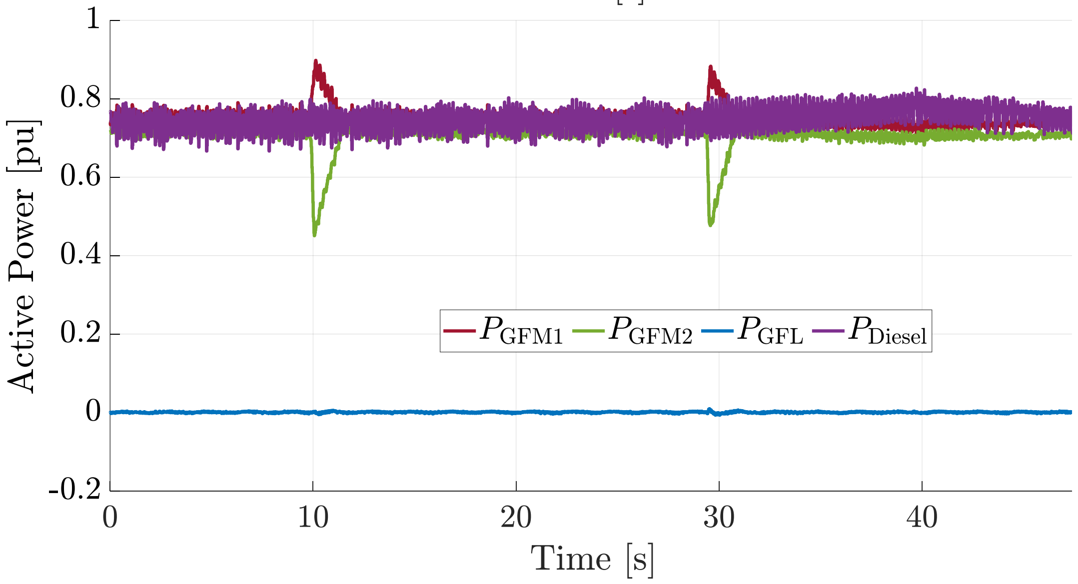
$$H = 0.475\ kWs/kWVA$$

Secondary Control—Frequency



$f_1^* = f_2^* = f_3^* = 60 + m * P * 60$ (m is the droop percentage)

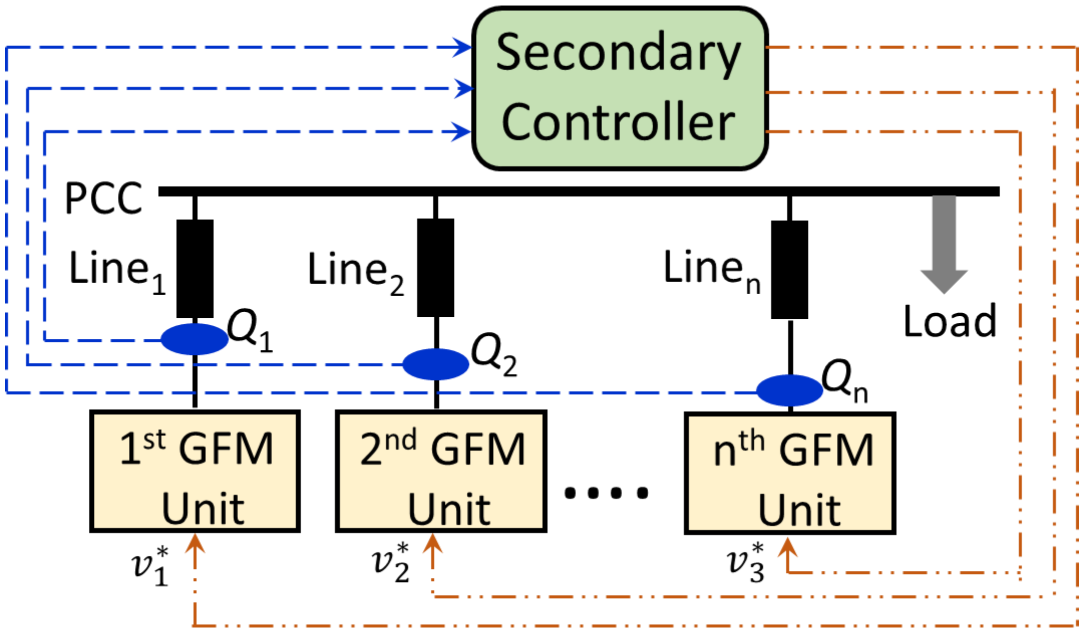


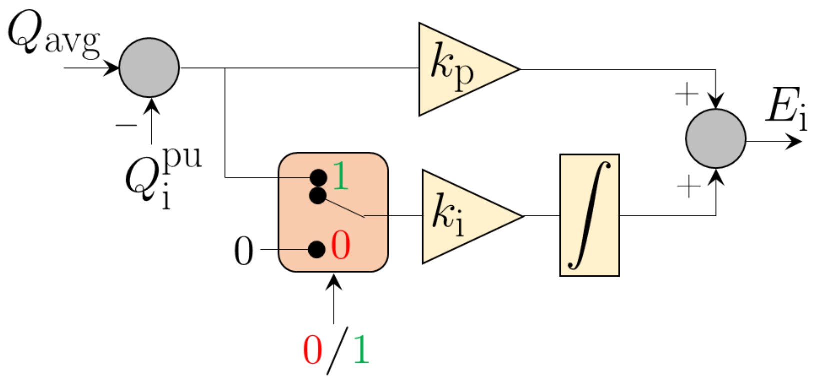


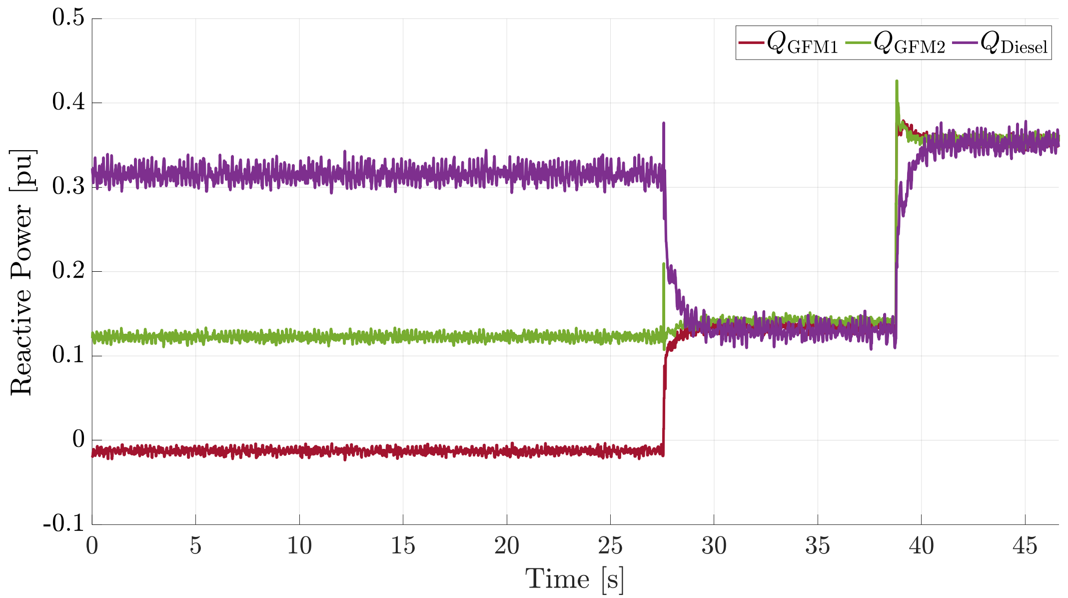
Testing results:

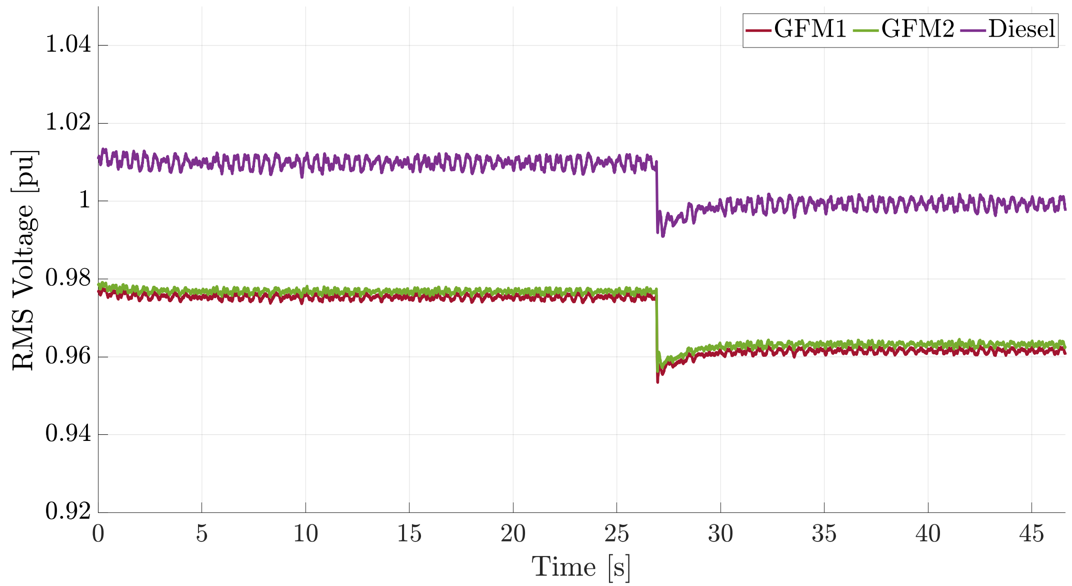
- The frequency is regulated to the nominal values.
- No competing effect and all regulate into the nominal frequency.

Secondary Control—Voltage









$$v_i^* = v^* - n * Q + E_i$$

$$Q_{\mathrm{avg}} = \frac{1}{n}\left(\frac{Q_1}{S_1} + \frac{Q_2}{S_2} + \cdots + \frac{Q_\mathrm{n}}{S_\mathrm{n}}\right)$$

Overview of ESIF Lab

Section 2

Section 4

Grid simulator

PCC switch

Section 3

Diesel

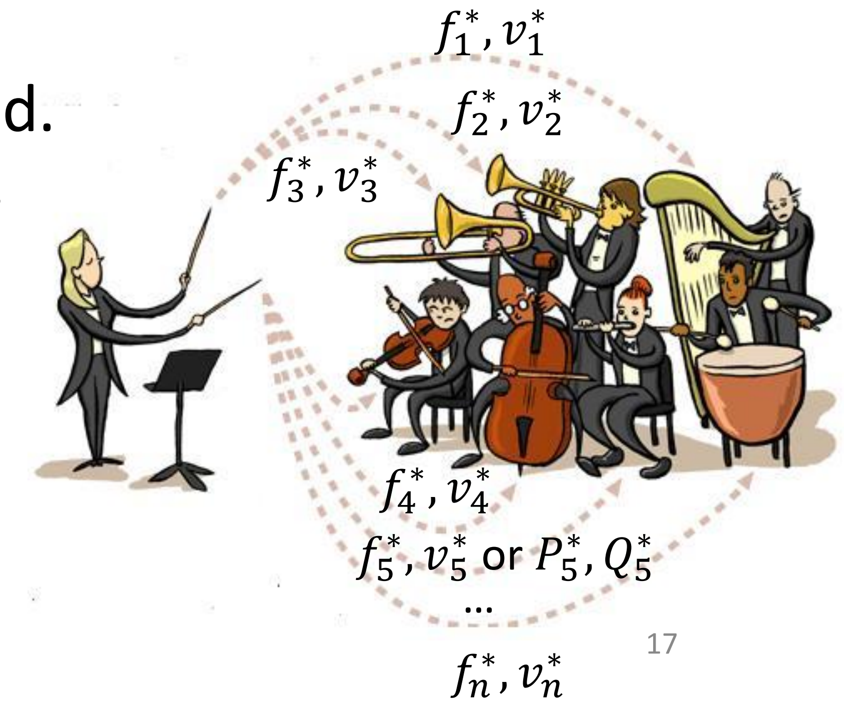
Section 1

Load bank

Photos by NREL

Key Learnings and Findings

- Frequency and voltage droop need to be characterized.
  - There are different droop languages that should be unified.
- Tuning the droop slope can easily cause (or prevent) stability issues.
- Through adjusting the inverter droop intercept, we can:
  - Perform secondary control.
  - Dispatch the GFM inverter to output the desired power.
  - **Dispatch GFM inverters like we dispatch GFL inverters** (in parallel with diesel and grid-connected operation).
- Reactive power sharing can be a problem—without proper control, the use of reactive power can unexpectedly de-rate the inverter output.
- GFM inverters have similar output impedance.



KEY FINDING:
Interoperability and dispatch of GFM inverters is all about droop!

Thank you!

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