unifi consortium
universal interoperability for grid-forming inverters

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Comprehensive Laboratory Evaluation of Multi-vendor Grid-forming (GFM) Inverters

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Acknowledgement and Disclaimer

Acknowledgement

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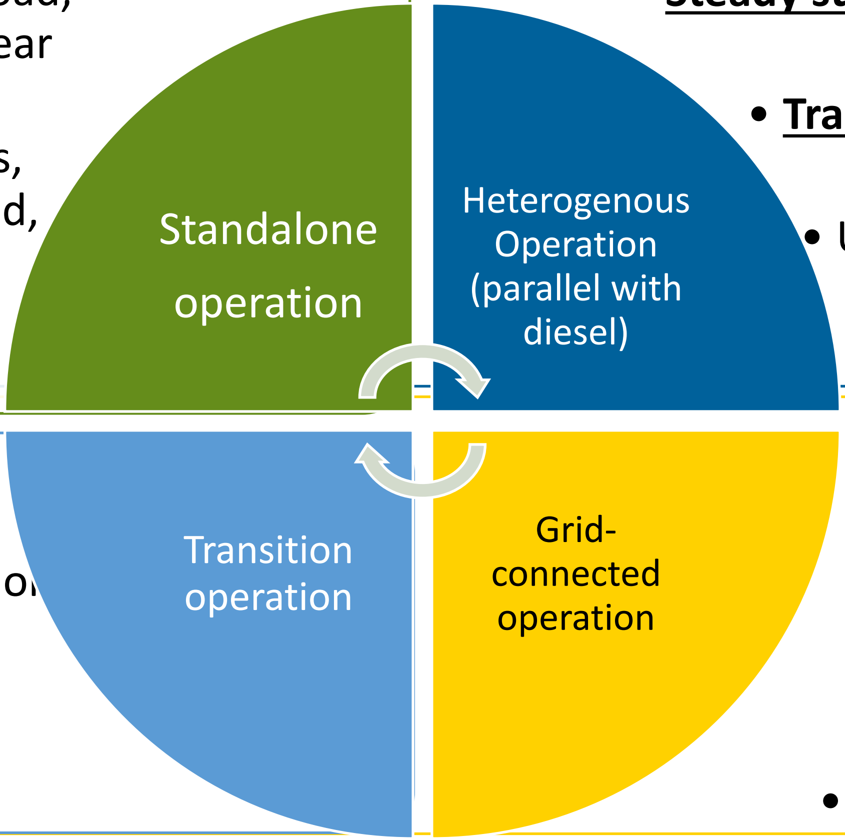
Goal of UNIFI multi-vendor GFM Inverter Evaluation

- There is a lack of standard testing protocol for 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 of GFM inverters (standalone, heterogenous operation, grid-connected and transition operation)
  - Use findings to drive GFM Specifications
- Provide findings and guidelines for industry and academia
  - How to configure and control the GFM inverter?
  - What are the research gap?

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

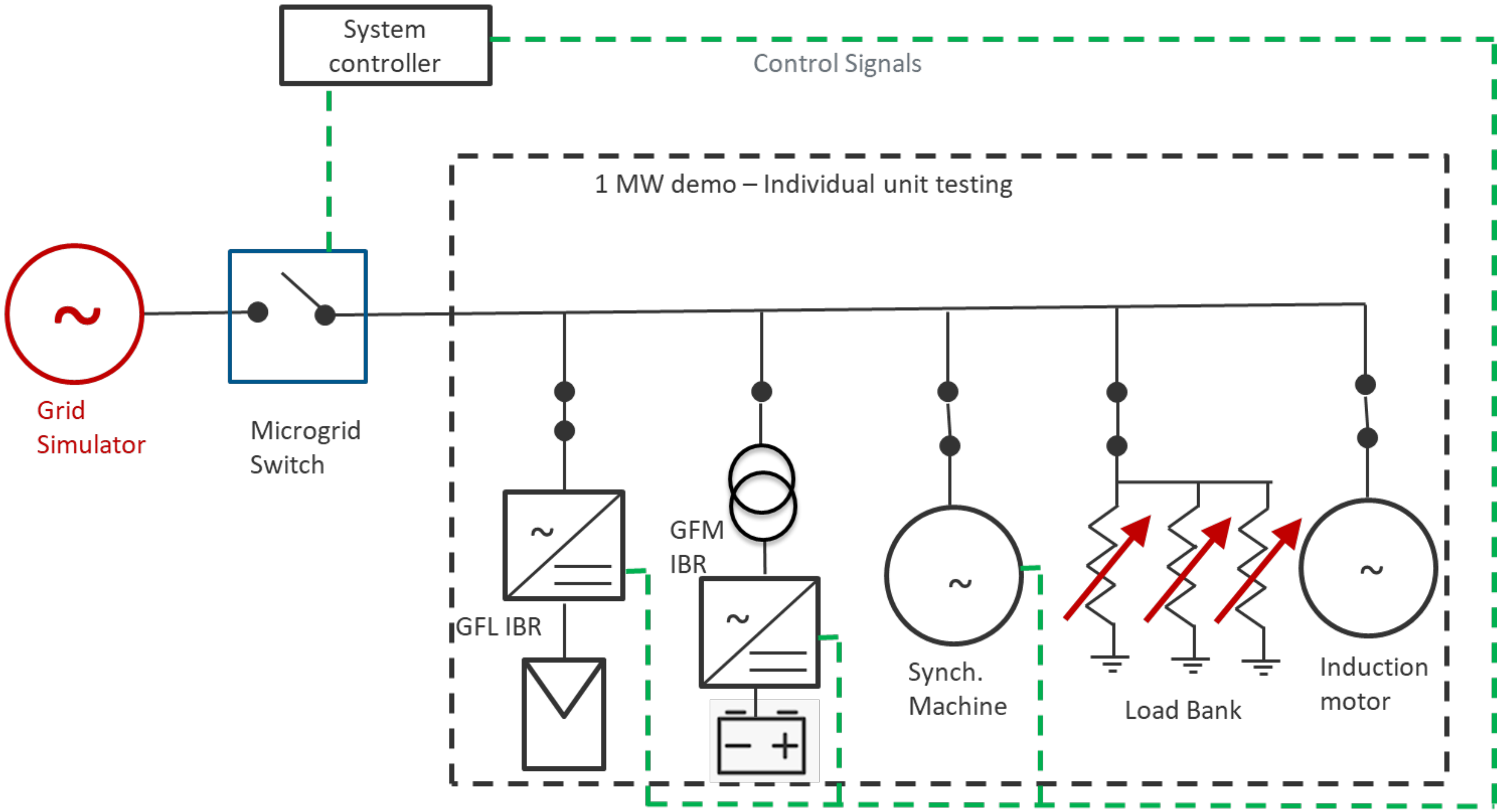


- Synchronization operation
- Islanding operation

- **<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

Testing circuit



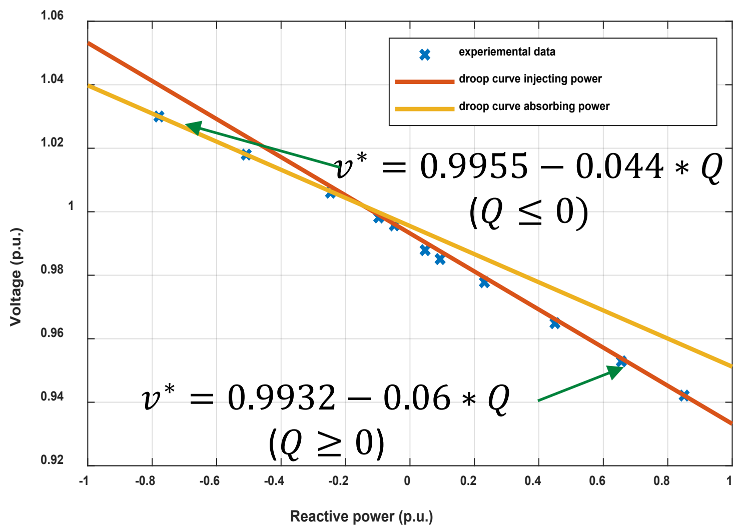
- The same testing circuit for easy configuration and testing
- The same testing protocol for fair comparison
    - Power quality
    - Overloading capability
    - Transient stability
- A system controller to dispatch all the elements

Inverter specification

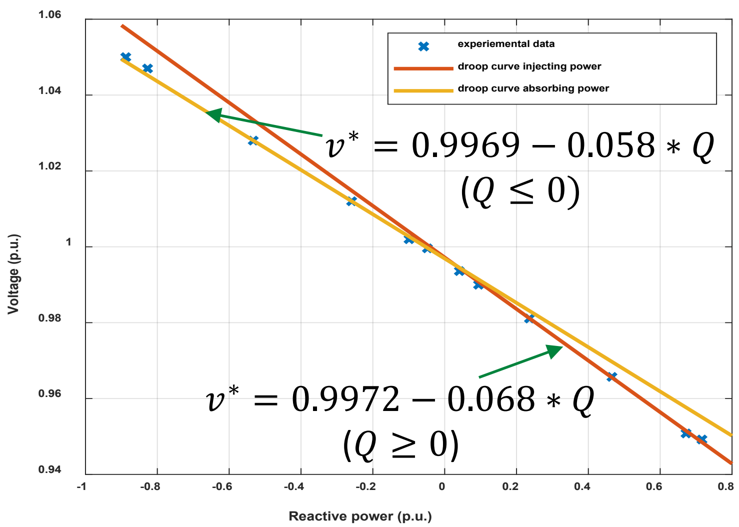
Specification	GFM#1	GFM#2	GFM#3
Frequency droop settings	0.25%	0.1 Hz gives 7.8 kW at 500	0.5 Hz
Frequency droop	0.25%	0.67%	0.83%
Voltage droop settings	5%	10 V gives 7.22 kVAR for 2160	24 V
Voltage droop	5%	6.48%	5%
Synch check	Yes (GCB and MCB)	No	Yes (GCB)
Secondary control	Yes	Yes	Yes
Operation mode	GFM, GFL, and grid-supporting control	GFL and GFM control	GFL and GFM control
Communication protocol	Modbus TCP		

Characterization of droop (v-q)

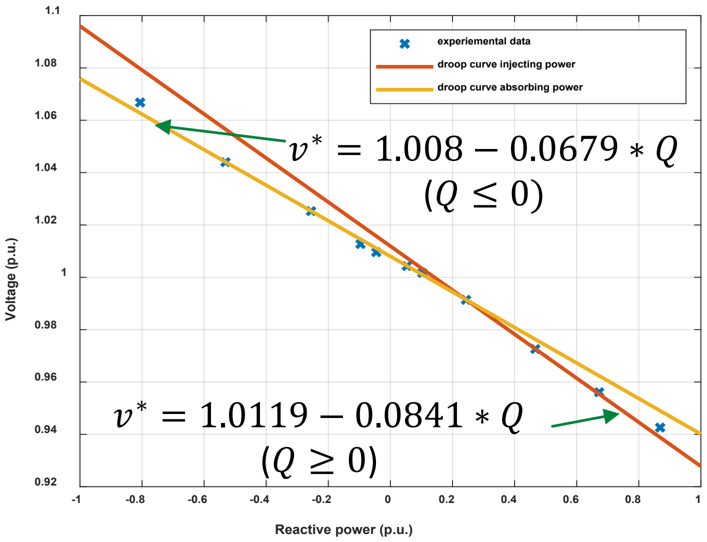
GFM #1 voltage droop characterization



GFM #2 voltage droop characterization



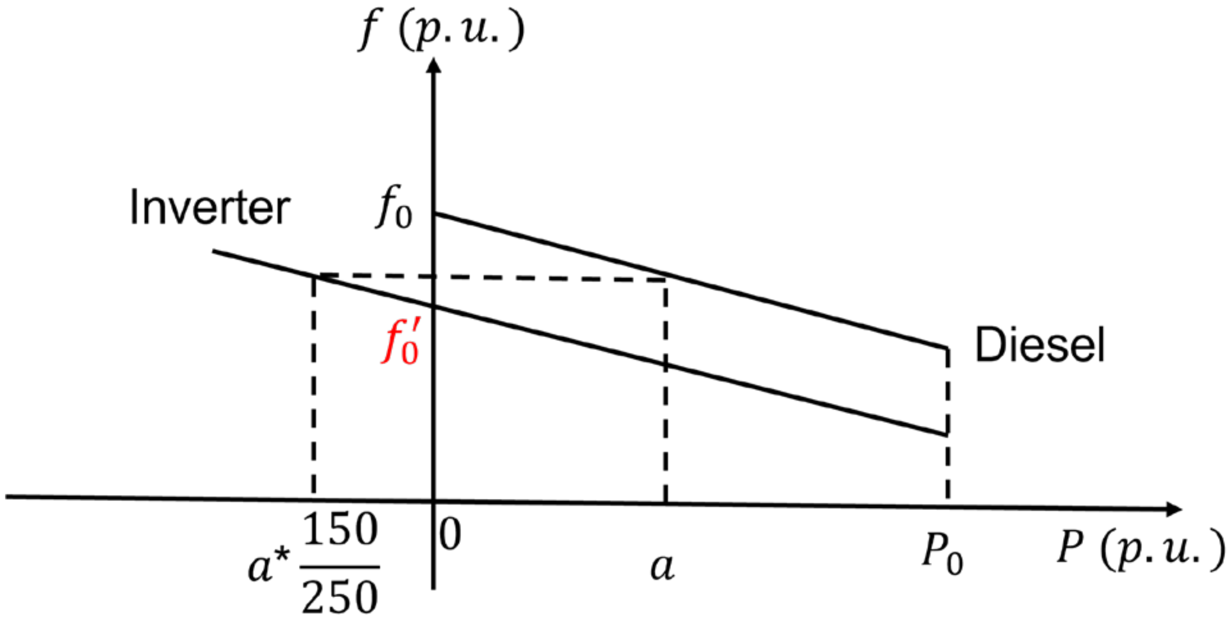
GFM #3 voltage droop characterization



Learnings and findings:

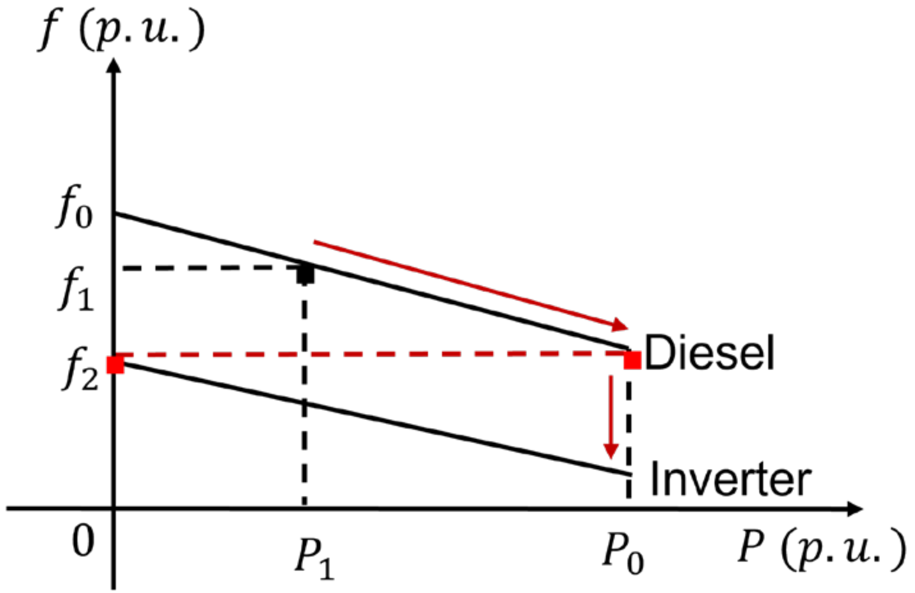
- Voltage droop coefficients are not the same as the defined value
  - Injecting and absorbing reactive power have different droop characteristics
    - Injecting reactive power: intercept is lower than “1” p.u., and droop slope is higher than the defined value
    - Absorbing reactive power: intercept is lower than “1” p.u., and droop slope is lower than the defined value
- Transformer is the main reason results in this droop characteristics
- This droop characterization is very important because a lot of testing depends on accurate droop characteristics (secondary control, parallel with diesel, grid-connected, transition operation with PF 0.8 lagging and leading load).

Configuraiton of the GFM inverter for heterogenous operation



$$f_0' = 60 - 60 * 0.006 * (0.25 + 0.15) \text{ (a=0.25)}$$

Example of inverter sinking power from diesel

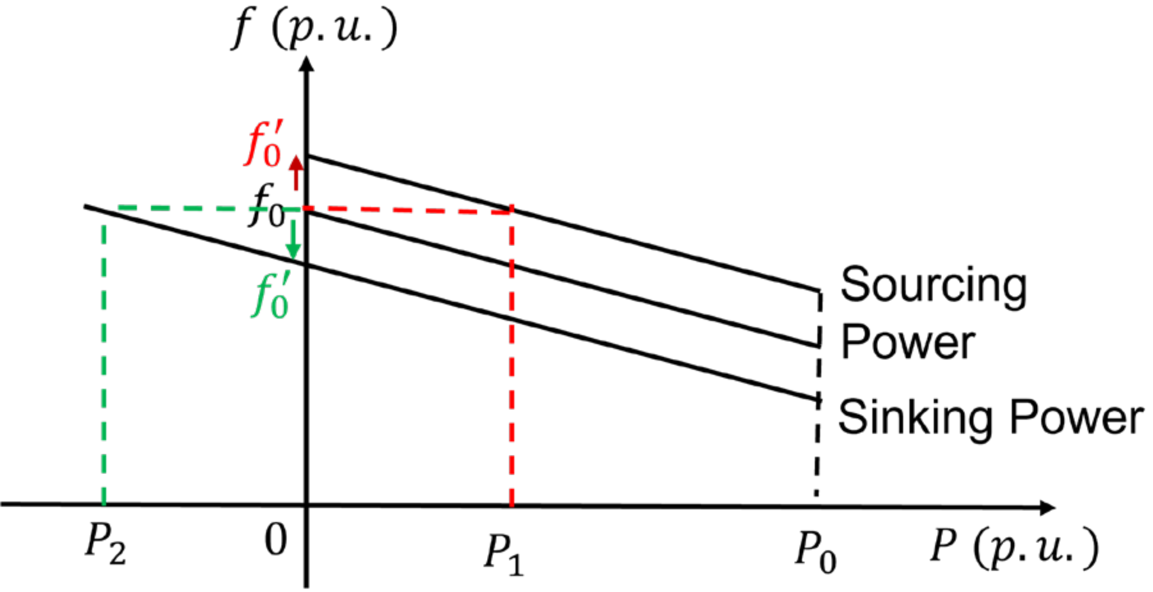


$$\Delta f = m * 60 * (P_{new} \text{-} P_{old})$$

Example of unequal power sharing between diesel and inverter

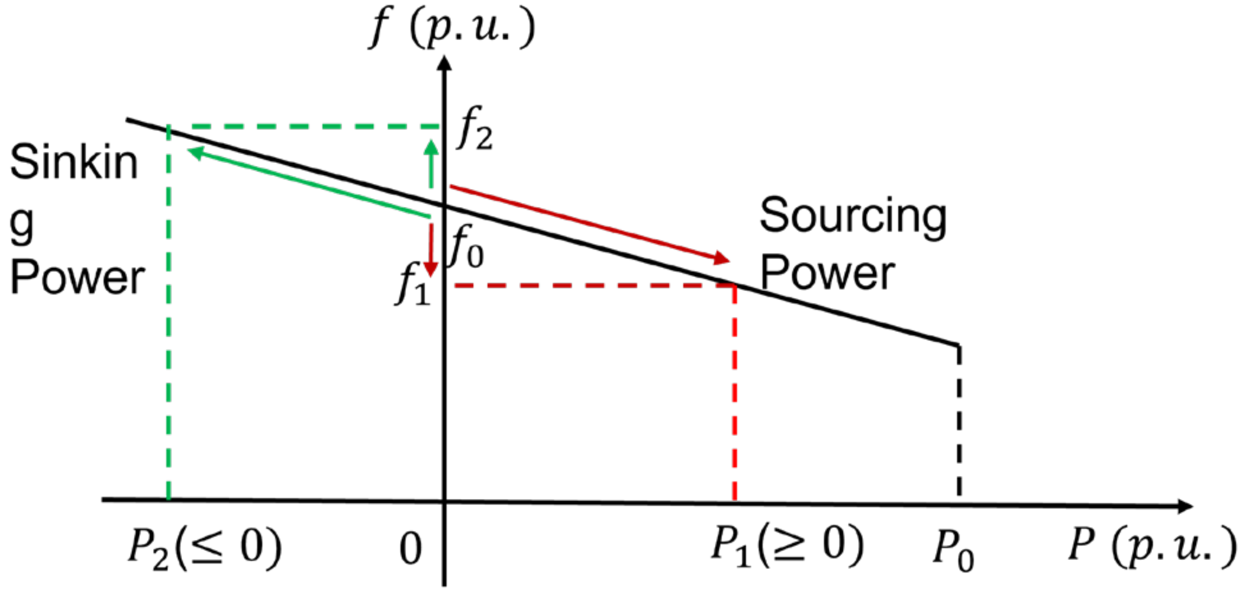
We can dispatch the GFM inverter like we dispatch the GFL inverter!

Configuraiton of the GFM inverter for grid-connected operation



$f_0' = 60 - 60 * 0.006 * (P_1 - 0)$ (e.g., P_{new}= P_1 and $P_{old} = 0$)

Example of changing inverter frequency droop intercept to sourcing/sinking power



$f_1 = 60 - 60 * 0.006 * (P_1 - 0)$ (e.g., P_{new}= P_1 and $P_{old} = 0$)

f_1 and f_2 are grid simulator stepped frequency

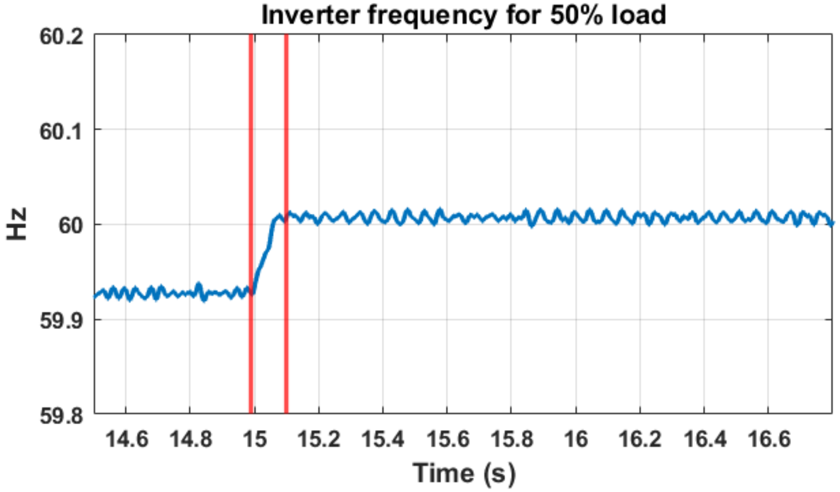
Example of grid simulator stepping up/down frequency to let inverter sourcing/sinking power

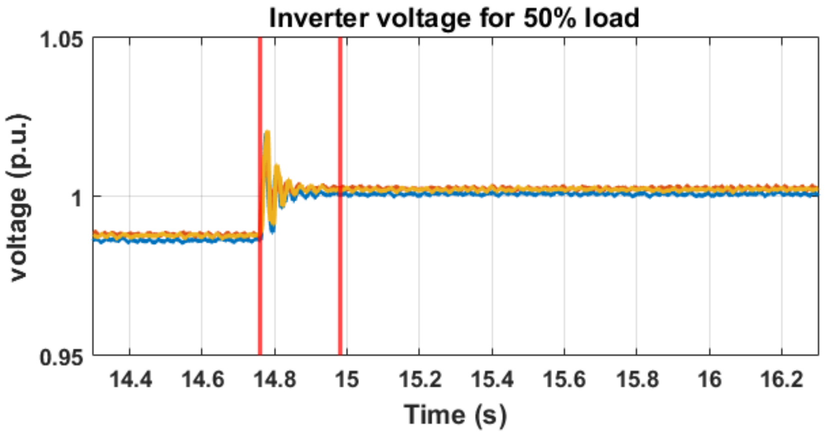
We can dispatch the GFM inverter like we dispatch the GFL inverter!

Summary of testing results

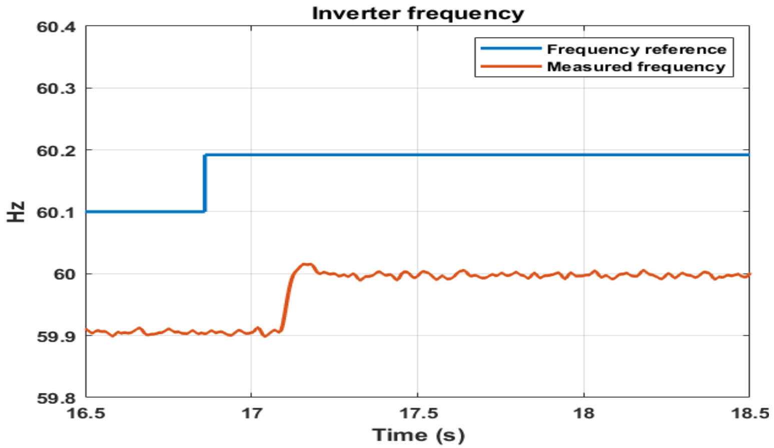
Example standalone secondary control (50% loading)

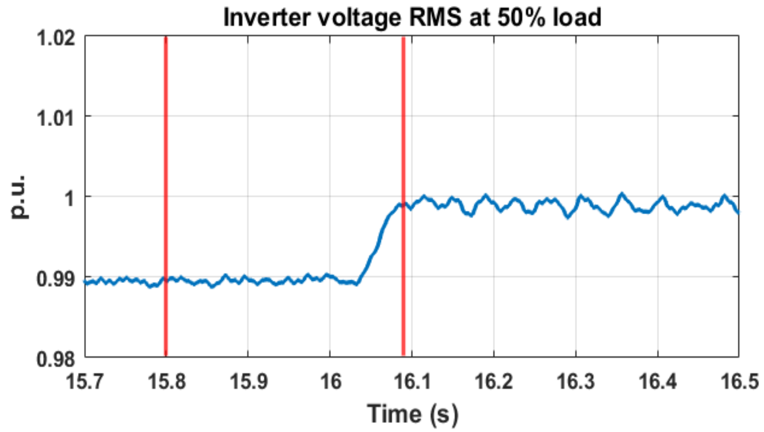
GFM#1



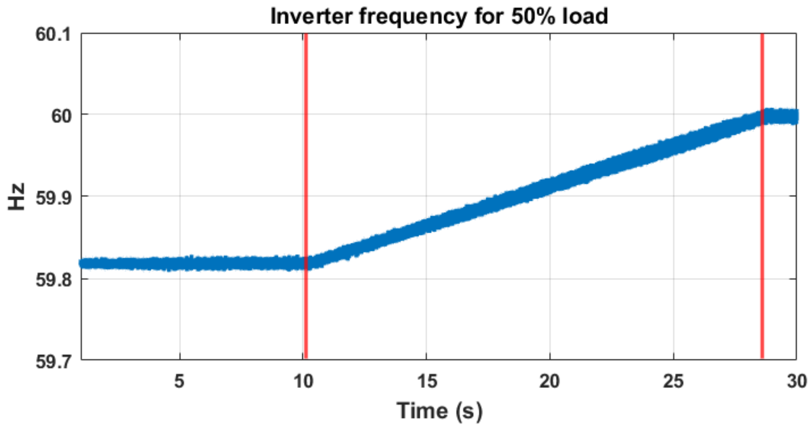


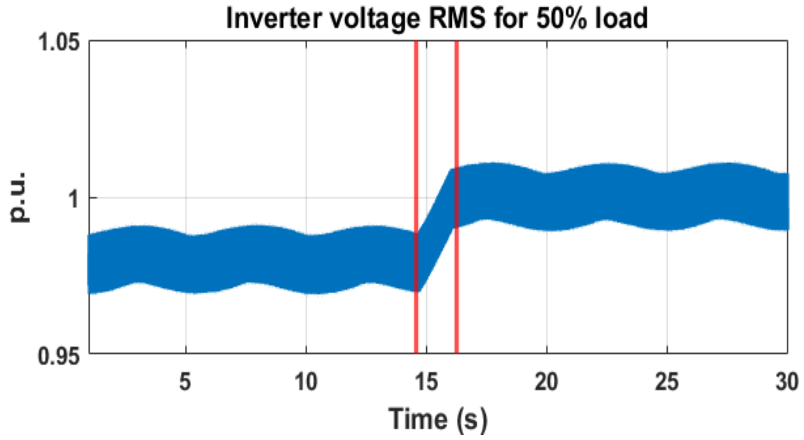
GFM#2





GFM#3

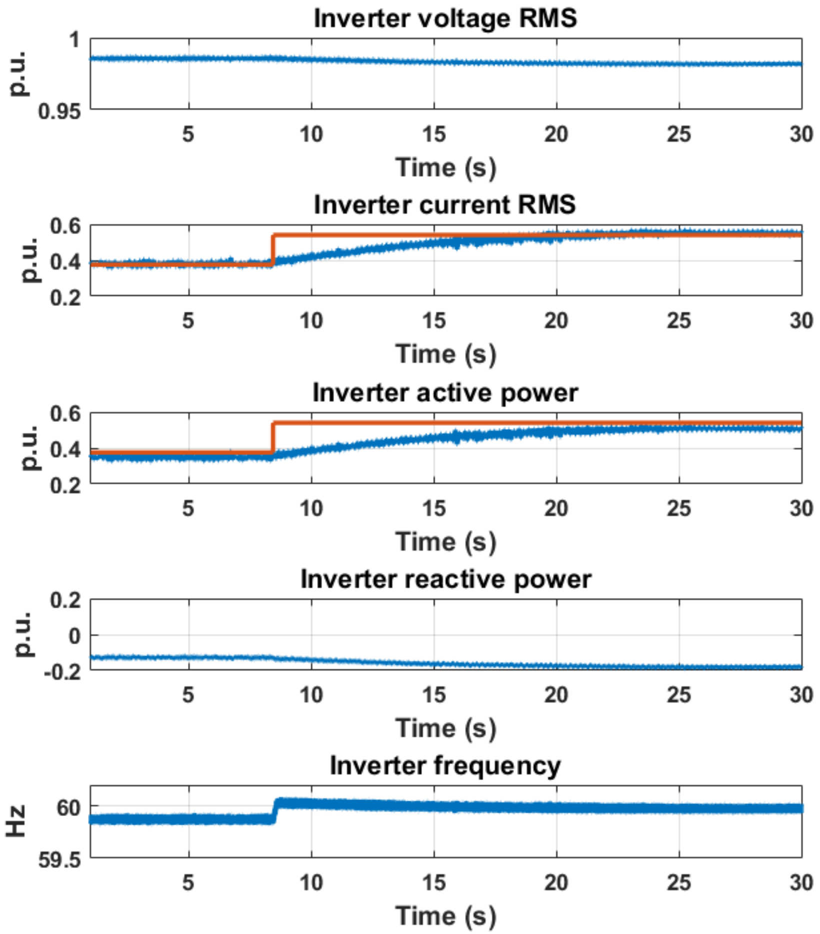


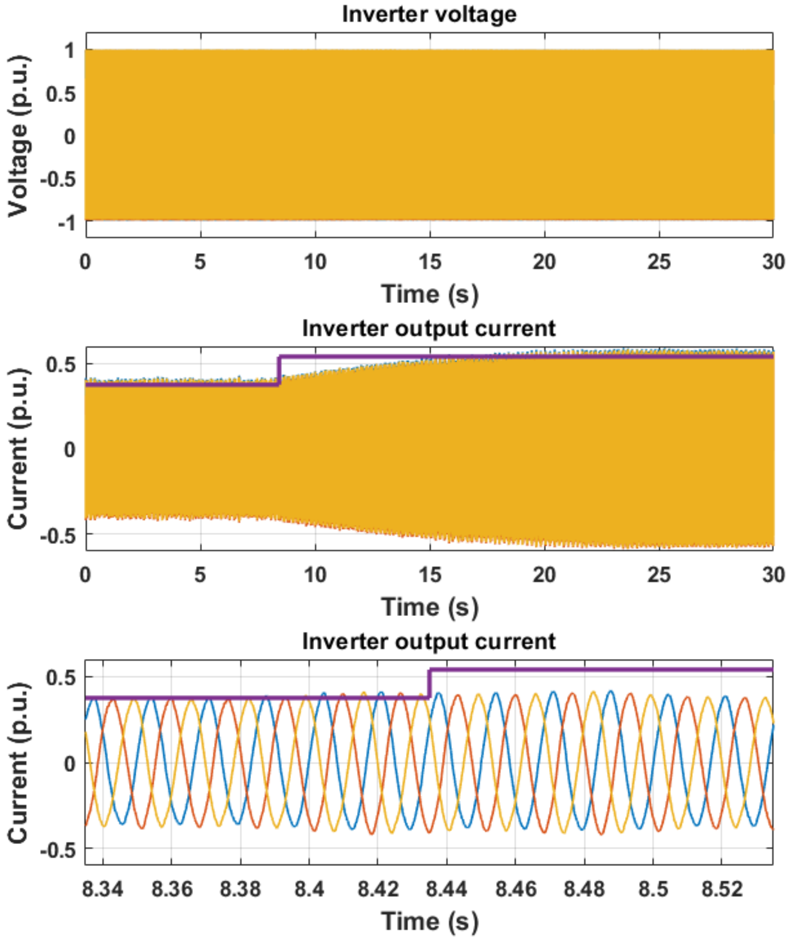


Summary of testing results

Example heterogenous operation: GFM #1 steps from equal power sharing to take 90% load

- Only one step is needed
- $\Delta f = 0.6\% * (0.54 - 0.1) * 60 = 0.1584 \approx 0.16\ Hz$





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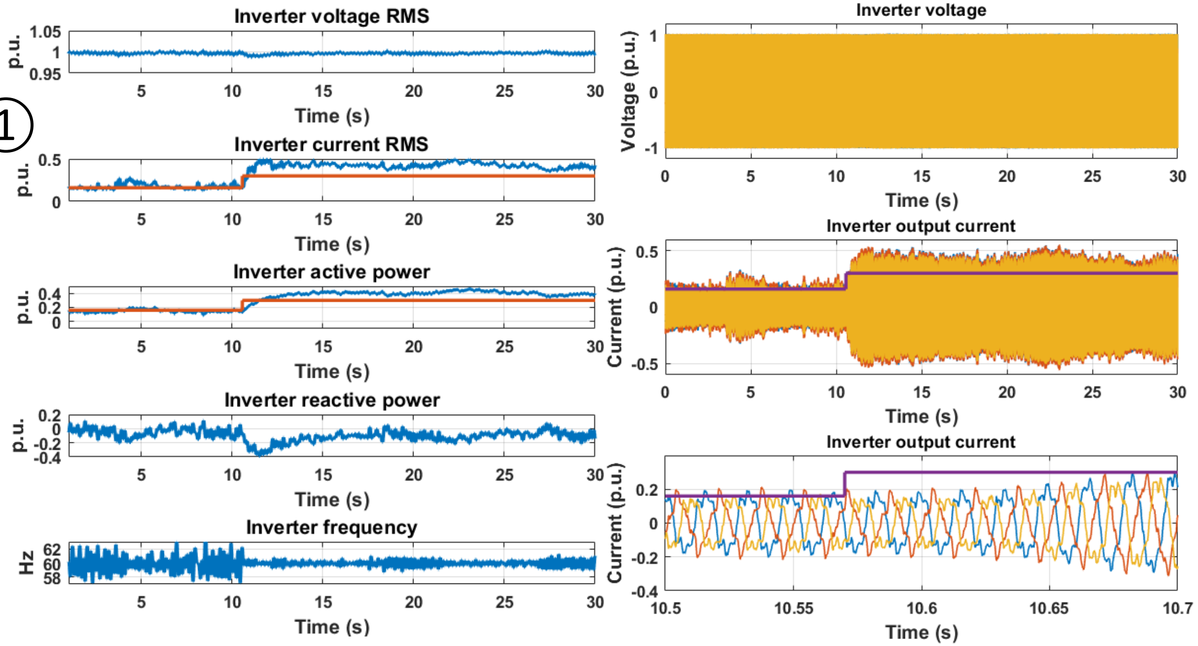

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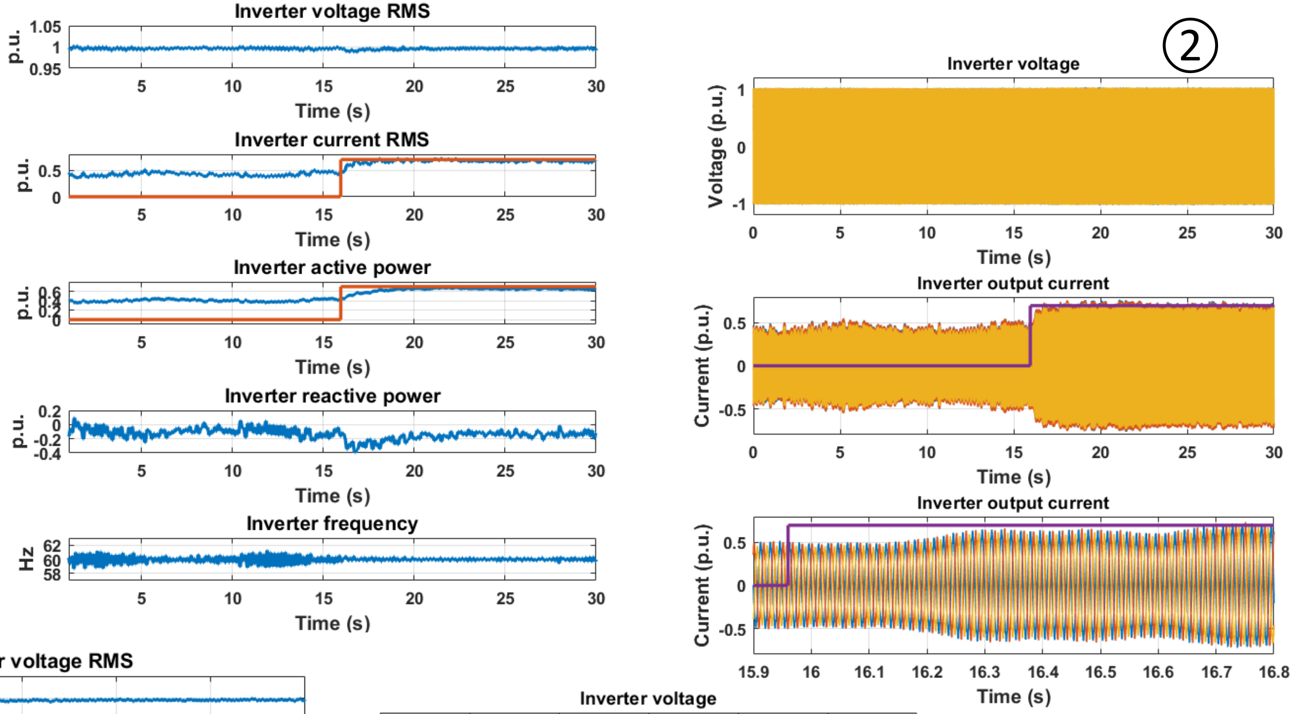
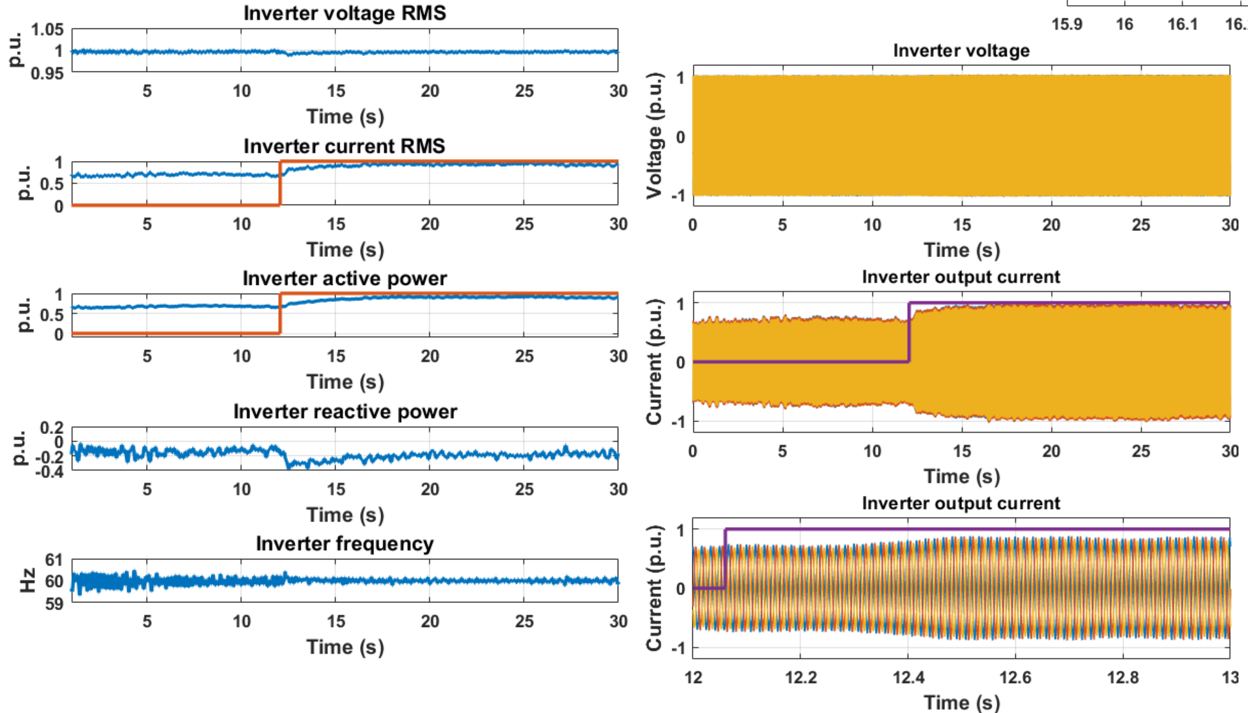


GFM #2 steps from equal power sharing to take 90% load

- Three steps are needed due to the large frequency intercept step
- $\Delta f = 0.6\% * (0.9 - 0.02) * 60 = 0.324\ Hz$
- Each step is 0.11 Hz

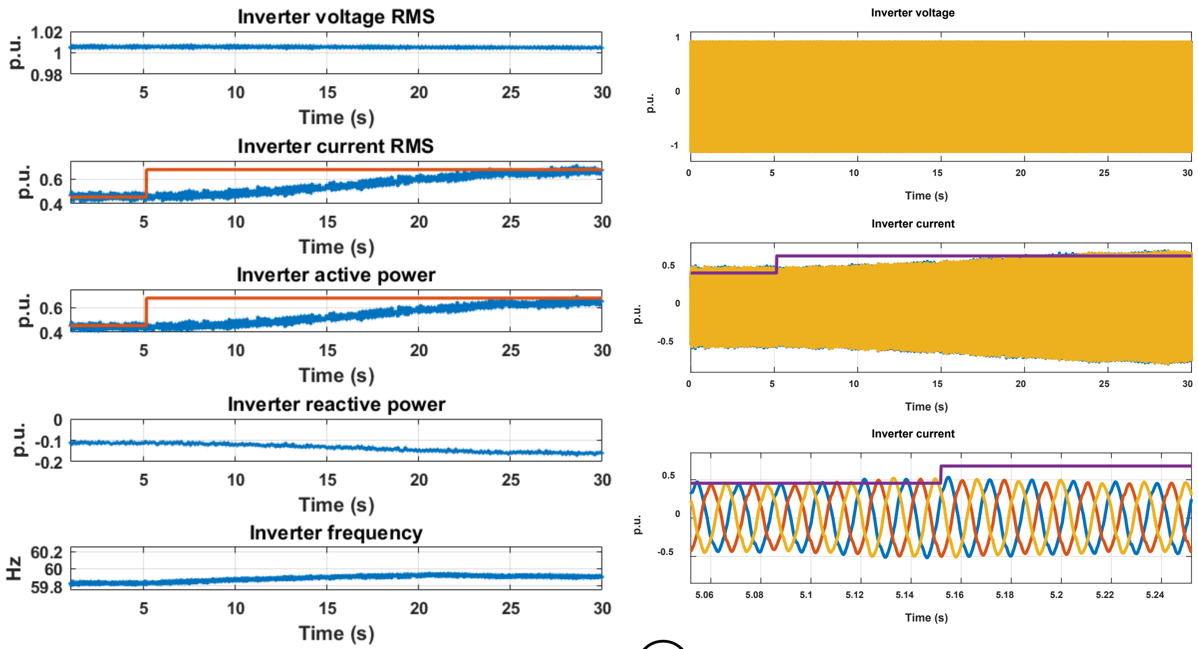
③



Summary of testing results

GFM #3 steps from equal power sharing to take 90% load

- Two steps are needed due to the large frequency intercept step
- $\Delta f = 0.6\% * (0.9 - 0.083) * 60 = 0.2941\ Hz$
- Each step is 0.15 Hz



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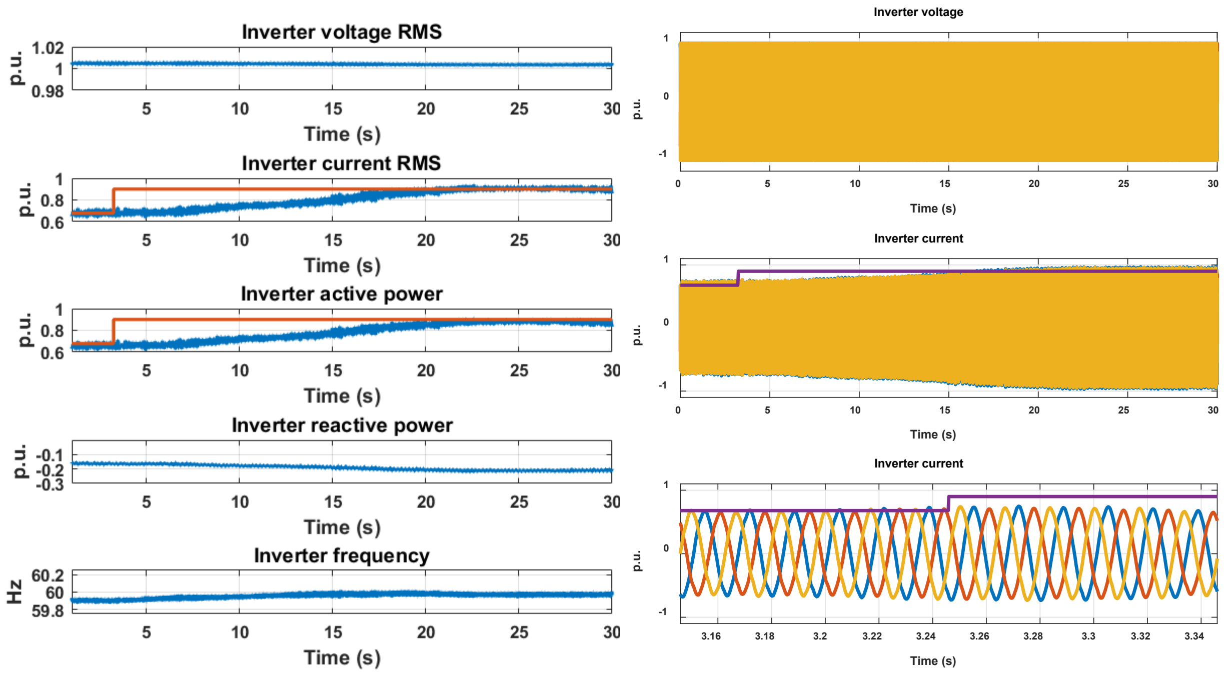

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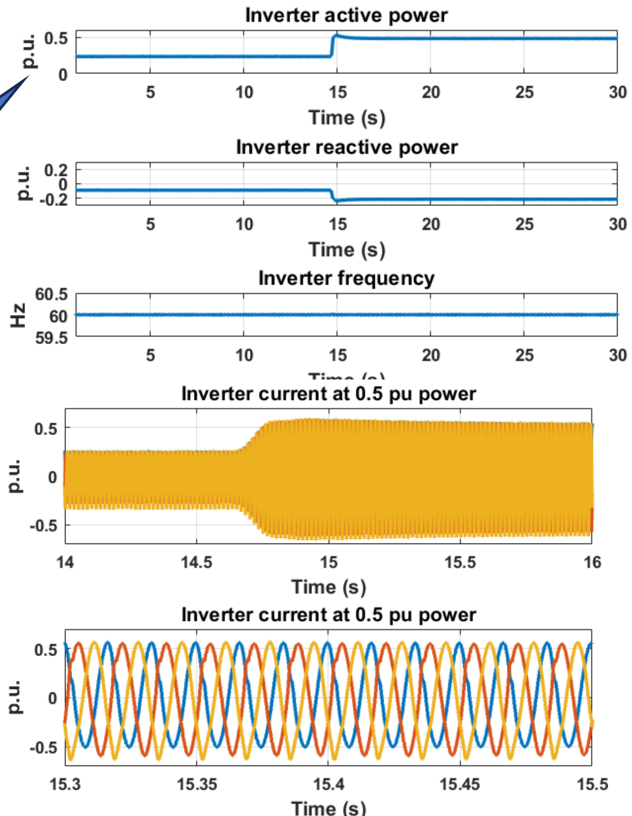
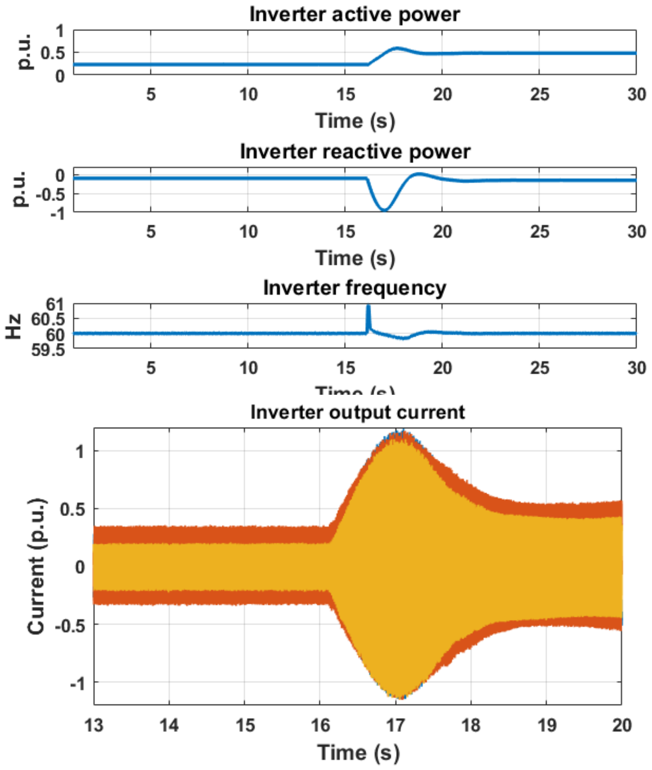
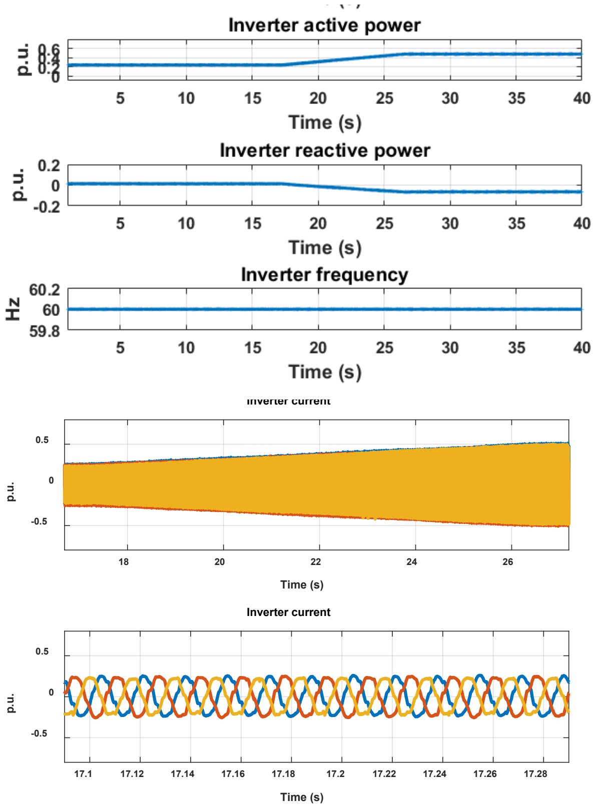
Sourcing Active Power	GFM #1	GFM #2	GFM #3
Capability to source active power	Output the expected active power except 100% (unexpected reactive power -0.42 p.u. de-rate the inverter)	Output the active power slightly lower than the target value (e.g., 25% output 23%)	Output the active power slightly lower than the target value (e.g., 25% output 23%)
Oscillations/overshoots	Smooth increase, no overshoot, and no oscillations	No oscillation. But with large overshoot (2 times)	Smooth increase, no overshoot, and no oscillations
Inverter THD for voltage and current	Voltage: ≤0.5% Current: ≥5% (5%-50% loading)	Voltage: ≤0.35% Current: ≥5% (5%-25% loading)	Voltage: ≤0.7% Current: ≥5% (5%-50% loading)
Settling time	Les than 0.5 seconds	Between 2.5 seconds and 10 seconds	Between 2.5 seconds and 6 seconds

Example results dispatch inverter sourcing from 25% to 50% active power

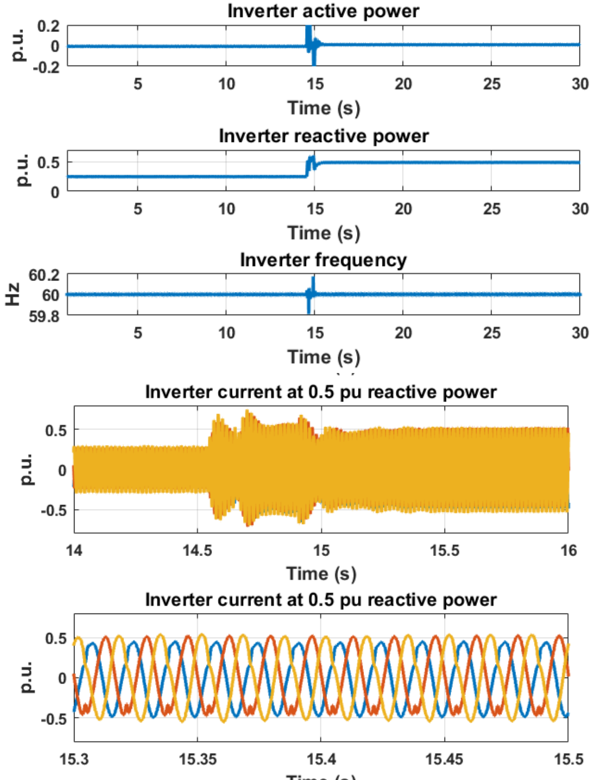


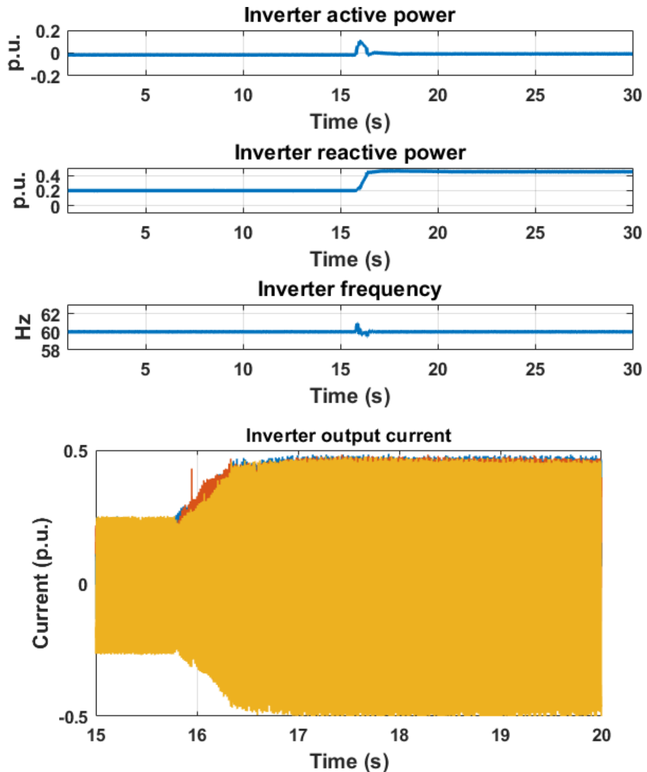


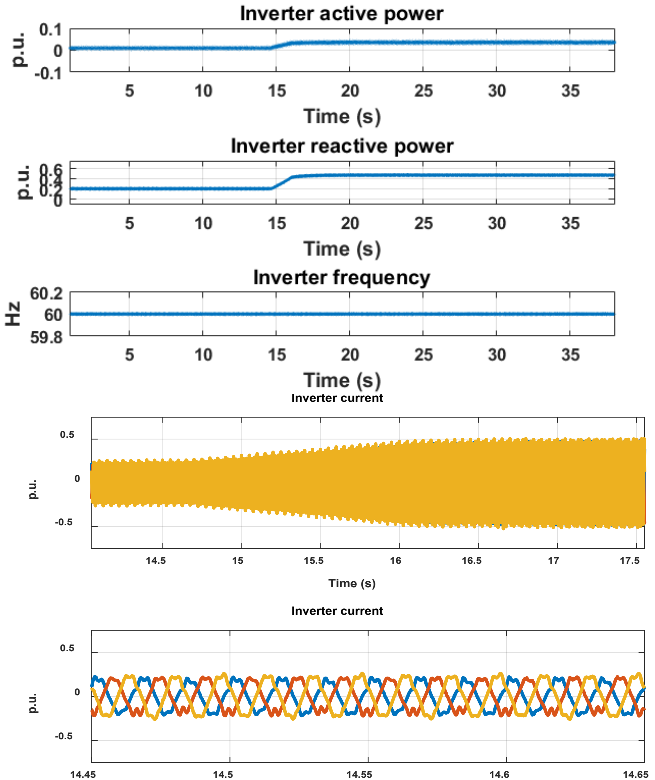


Sourcing Reactive Power	GFM #1	GFM #2	GFM #3
Capability to source reactive power	Output the reactive power slightly lower than the expected value (e.g., 25% is 24%)	Output the reactive power slightly lower than the expected value (e.g., 25% is 20%)	Output the reactive power slightly lower than the expected value (e.g., 25% is 21%)
Oscillations/overshoots in current	Exhibit oscillations when the voltage intercept is shifted up; the higher the reactive power, the larger the oscillations	Exhibit transient oscillation and overshoot.	Smooth increase, no overshoot. But there is constant oscillations. Very distorted waveform even with higher power.
Inverter THD for voltage and current	Voltage: ≤0.6% Current: ≥5%	Voltage: ≤0.6% Current: ≥5%	Voltage: ≤0.6% Current: ≥5%
Settling time	Les than 1 seconds	Less than 3 seconds	Less than 6 seconds

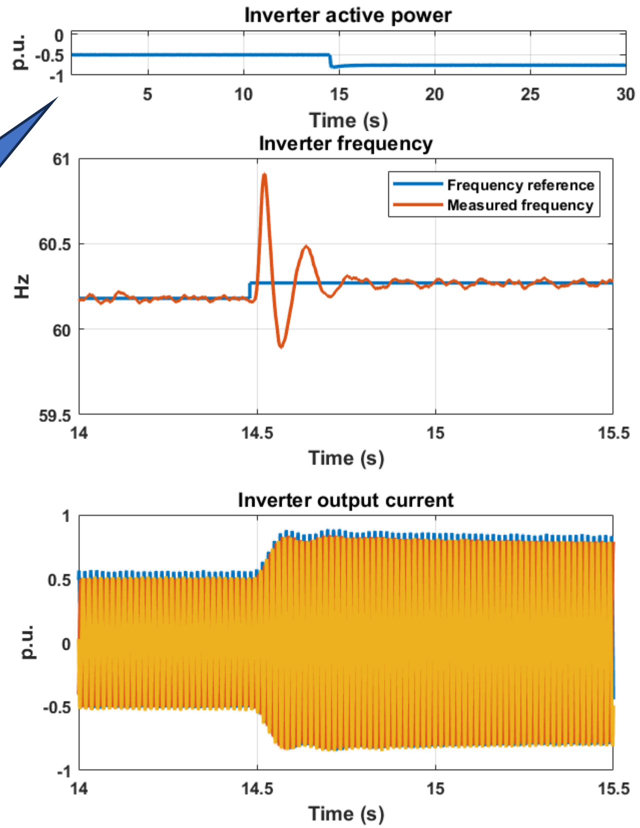
Example results dispatch inverter sourcing from 25% to 50% reactive power

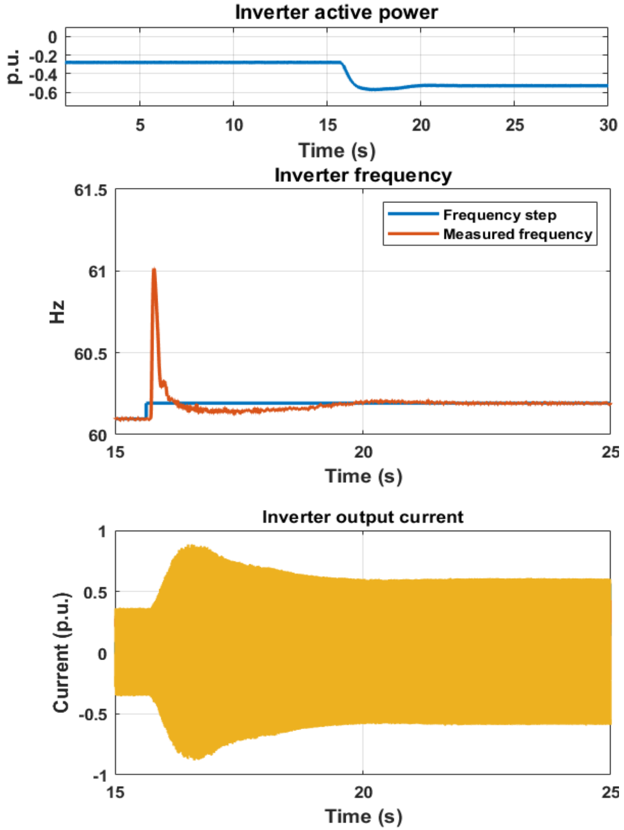


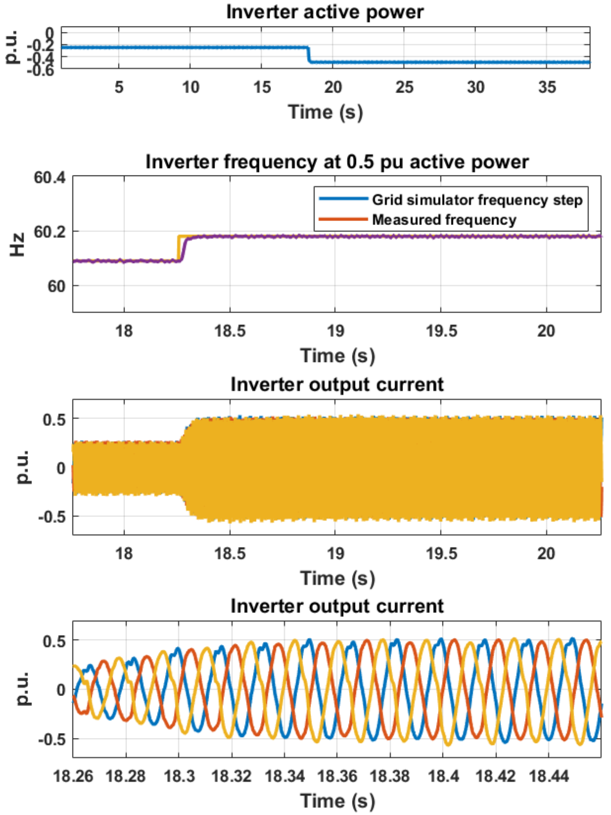




Grid sim step up frequency	GFM #1	GFM #2	GFM #3
Capability to sinking active power	Operate well for all loadings. Output the active power close to target value	Output power slightly higher than target value (e.g., 50% is 52%)	Trip at 100%. Output the active power slight lower than target
Reactive power output	Less than 0.3 p.u.	Less than 0.12 p.u.	Less than 0.21 p.u.
Oscillations/overshoots	No overshoot and transient oscillation	Big overshoot (e.g., 2 times)	Smooth increase
Inverter THD for voltage and current	Voltage: ≤0.5% Current: ≥5% (25% and 50%)	Voltage: ≥5% (for 50% and 75%) Current: ≥5%	Voltage: ≤0.6% Current: ≥5% (25%, 50% loading)
Settling time	Les than 0.8 seconds	Less than 6 second	Less than 1 second



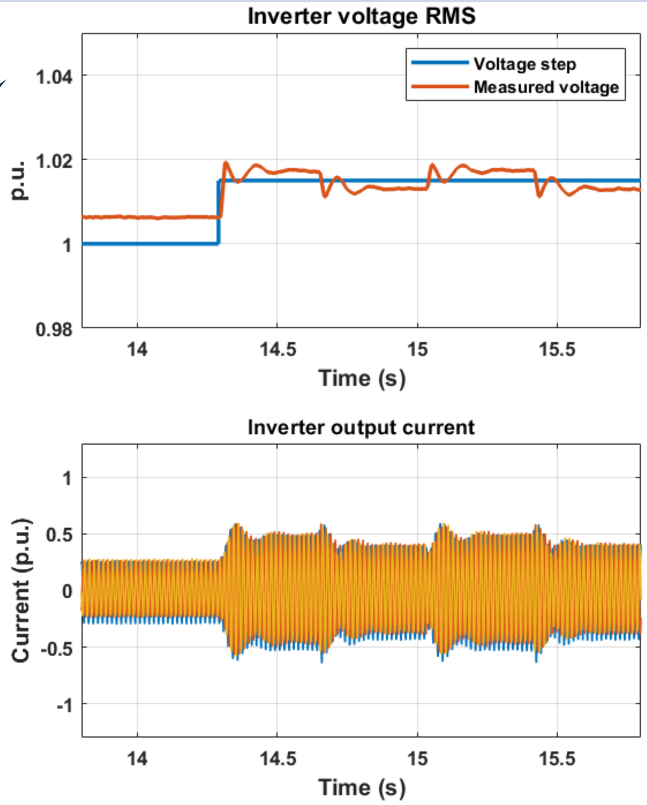


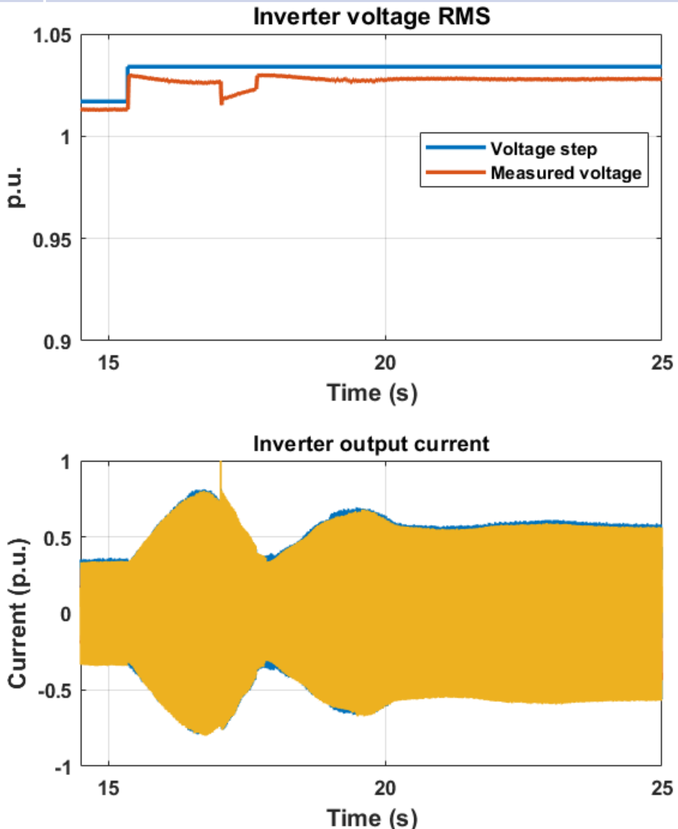


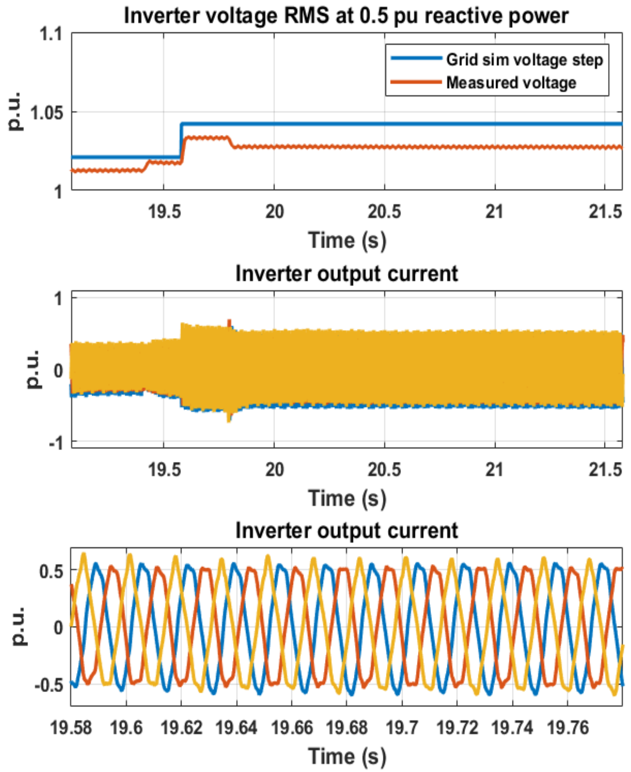
Example results dispatch inverter sinking from 25% to 50% active power

Grid sim step up voltage	GFM #1	GFM #2	GFM #3
Capability to sinking reactive power	Operate well for all loadings. Output the reactive power close to target value	Trip at 75%. Output reactive power higher than expected	No steady state at 25% and trip at 100%.
Active power output	Less than 0.12 p.u.	Less than 0.12 p.u.	n/a
Oscillations/overshoots	Exhibit overshoot and oscillation	Big overshoot (e.g., 2 times)	Smooth increase, no overshoot, and no oscillations
Inverter THD for voltage and current	Voltage: ≤0.5% Current: ≥5%	Voltage: ≤0.4% Current: ≥5%	Voltage: ≤0.6% Current: ≥5%
Settling time	n/a	n/a	n/a

Example results dispatch inverter sinking from 25% to 50% reactive power







Microgrid Transition Operation

Configuration	Test Type	Scenario	Power setting
Transition operation	Transient	Synchronization operation and islanding operation	Inverter supplies 50% load (PF=1, PF=0.8 lagging, and PF=0.8 leading), then synchronize to the grid simulator. Note down the transient wave form. When the system reaches steady-state in grid-connected mode, then perform islanding operation (make sure PCC power flow is close to zero).

Loading (50%)	Islanded	Synchronization Key strategy: PCC power flow is minimized and inverter maintains the same operating point (v, I, P, Q, f)	Grid-connected	Islanding (The same strategy as synchronization operation)
PF=1	Inverter with load	Before CB is closed, shift the frequency droop up by Δf=0.006*0.5*60=0.18 Hz.	Inverter supplies all the load	Inverter supplies all the load
PF=0.8 lagging	Inverter with load	Before CB is closed, shift the frequency droop up by Δf=0.006*0.4*60=0.144≈0.14 Hz, shift the voltage droop up by (0.0841*0.5*0.6-0.0119)*480=6.4 V	Inverter supplies all the load	Inverter supplies all the load
PF=0.8 leading	Inverter with load	Before CB is closed, shift the frequency droop up by Δf=0.006*0.4*60=0.144≈0.14 Hz, shift the voltage droop down by (0.0679*0.5*0.6+0.008)*480 =13.6 V	Inverter supplies all the load	Inverter supplies all the load

Learnings and finding of individual inverter testing

- Frequency and voltage droop needs to be characterized
  - There are different droop languages which should be unified
- Tuning 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 desired power
  - **We can dispatch GFM inverters like we dispatch GFL inverters** (parallel with diesel and grid-connected operation)
- Reactive power sharing can be a problem - without proper control, use of reactive power can unexpected de-rate the inverter output
- Need to know the acceptable droop intercept step for stable operation

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

Future Plans

- Develop a secondary control to achieve appropriate reactive power sharing by controlling the inverter terminal voltage
- Parallel the multiple GFM inverters with diesel and perform islanded operation, grid-connected operation, and transition operation (synchronization and islanding operation)
- Use an industrial controller (SEL RTAC) as the microgrid controller to dispatch all the elements

Publications

1. J. Wang, et al., “Experimental Characterization Test of a Grid-forming Inverter for Microgrid Applications,” IEEE ECCE 2023.
2. S. Ganguly, J. Wang, M. Shirazi, B. Kroposki, “Droop Control-Based Dispatch of an Islanded Microgrid With Multiple Grid-Forming Sources,“ IEEE IECON 2023.
3. J. Wang, S. Ganguly, B. Kroposki, “Study of Seamless Microgrid Transition Operation Using Grid-Forming Inverters,” IEEE IECON 2023.

Thank you

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