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Experimental Characterization Test of a Grid-Forming Inverter for Microgrid Applications

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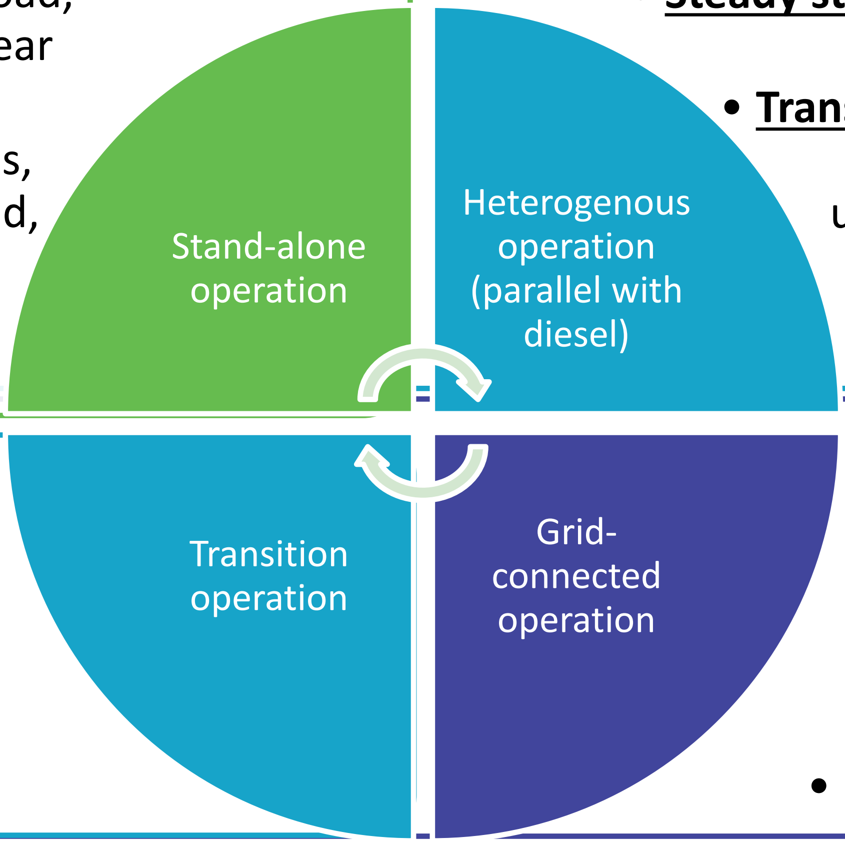
Goal of UNIFI Multi-Vendor GFM Inverter Evaluation

- 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 of GFM inverters (stand-alone, 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 gaps?

High-Level View of Testing Scenarios

- **<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 steps, 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

Hardware Experiment Test Setup

- <u>GFM inverter specs.:</u>
  - 250 kVA, need a delta:wye transformer
  - GFM (VF), GFL (PQ), and grid-supporting control (VF/PQ) control.
- <u>Testing circuit (microgrid):</u>
  - Grid simulator (540 kVA)
  - PCC switch
  - GFL inverter (125 kVA)
  - Diesel (187.5 kVA)
  - Load banks (500 kVA).
- <u>Control and communication:</u>
  - Configure the GFM inverter to always operate in GFM control.
  - Modbus TCP
  - Heartbeat, voltage, and frequency droop intercept, and droop slope (Modbus register map).

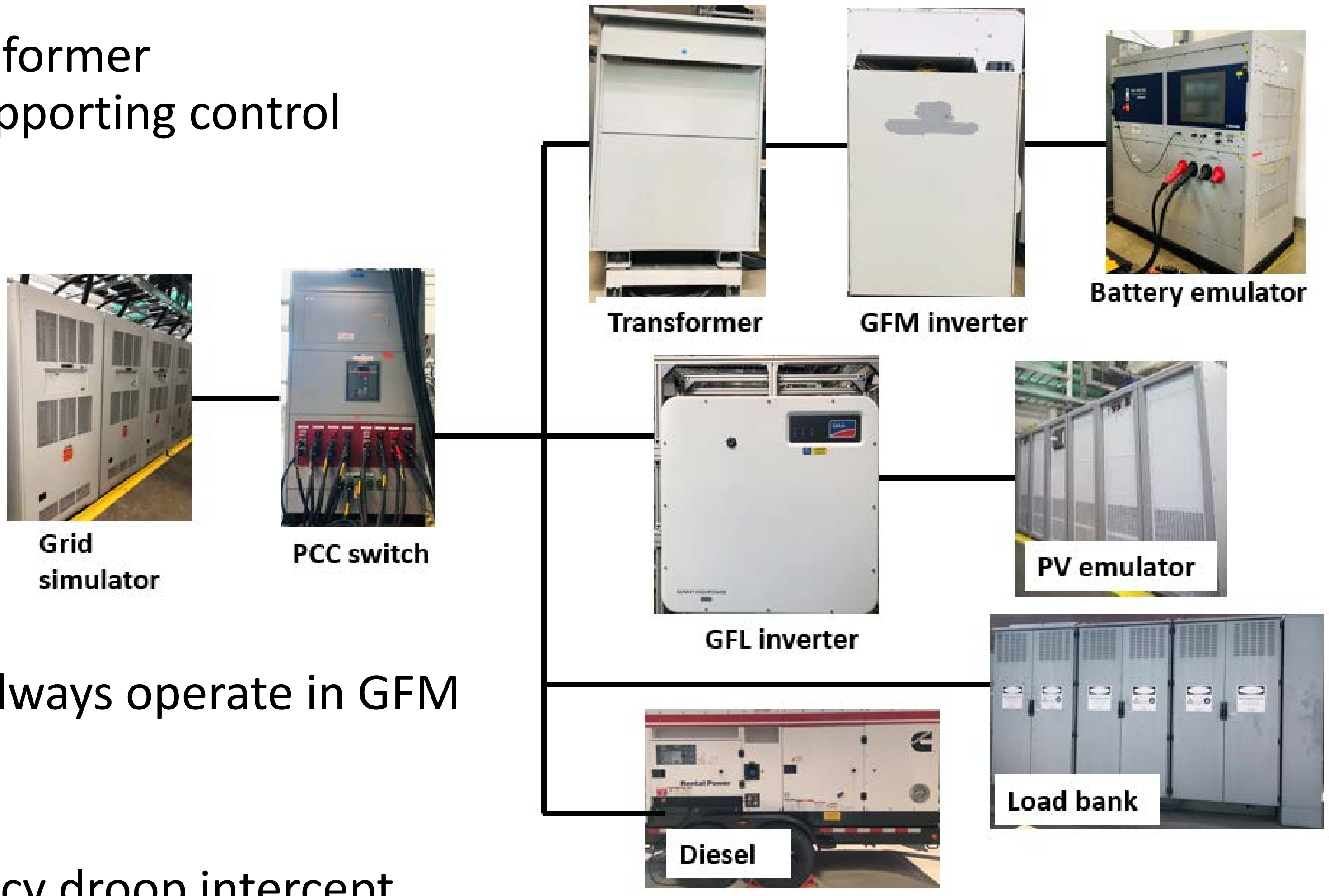
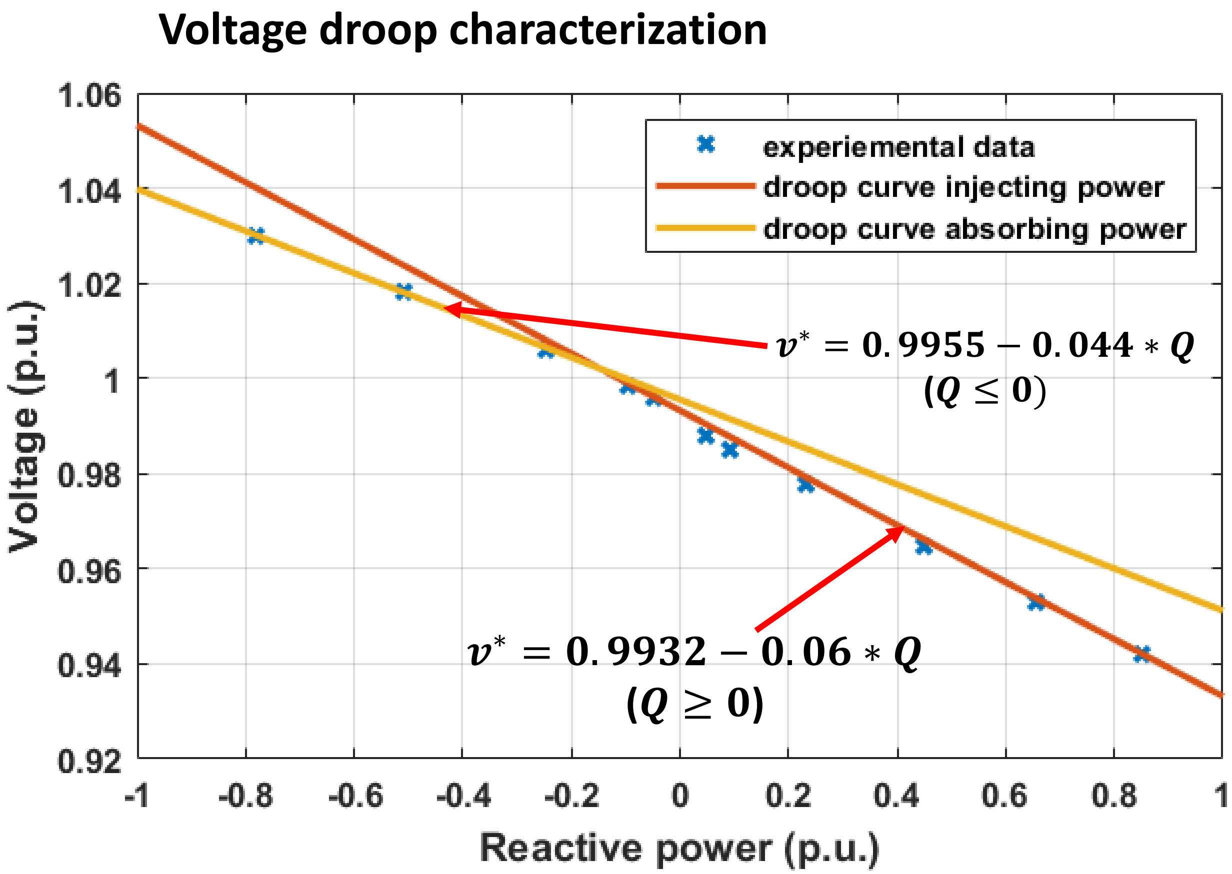


Photo credit: NREL

TESTING CONFIGURATION

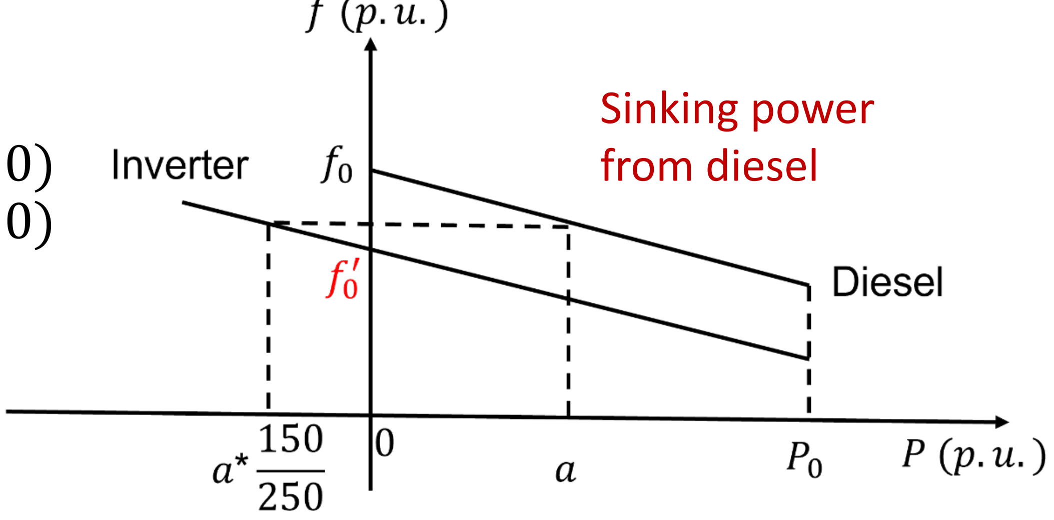
- Configure the droop settings:
  - Frequency droop: 0.25%
    - 60 Hz
    - Disable the coupling with reactive current/power (default).
  - Voltage droop: 5%
    - 480 V (1 p.u.)
    - Disable the coupling with active current/power.
- Verify the droop characteristics:
  - Frequency droop matches the testing results.
  - Voltage droop is off due to the transformer.



TESTING CONFIGURATION

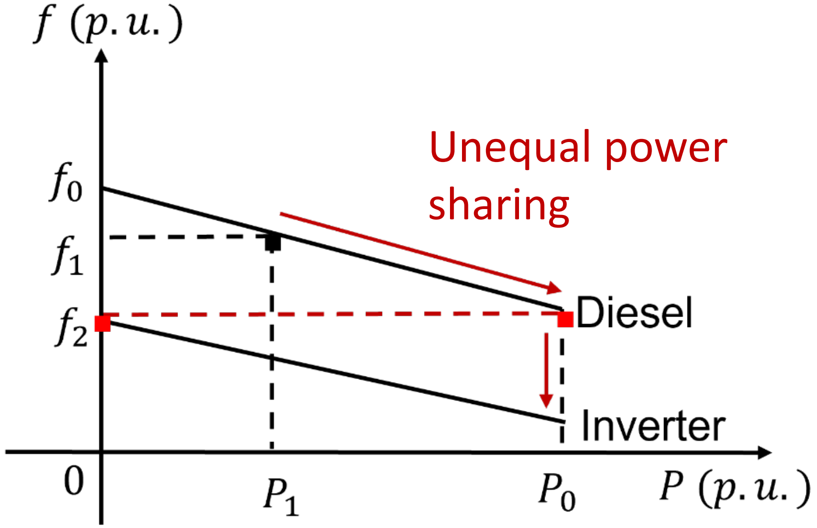
- Stand-alone islanded operation:

Secondary control
- $f_0 = 60 + m * 60 * P$
- $v_0 = 480 + n * 480 * P + (1 - 0.9932) * 480\ (Q \geq 0)$
  $v_0 = 480 + n * 480 * P + (1 - 0.9955) * 480\ (Q \leq 0)$



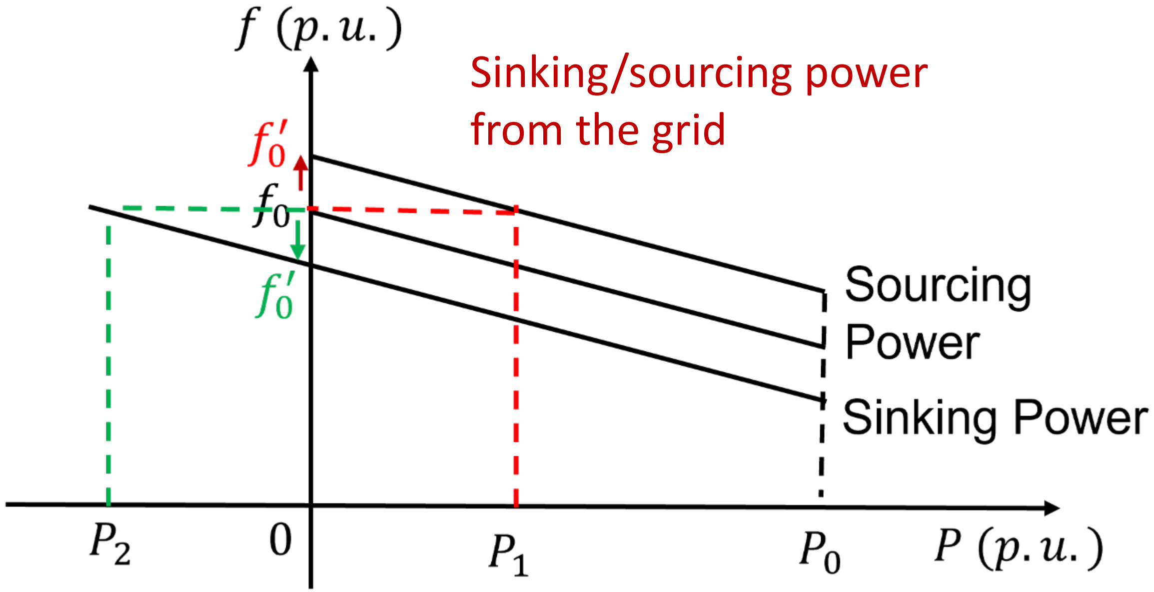
$f_0' = 60 - 60 * 0.006 * (0.25 + 0.15)$ (a=0.25)

- Heterogeneous islanded operation:
  - Diesel droop settings:
    - Frequency: 0.6%, -0.36 Hz representing 60 Hz
    - Voltage: 3.7%. 0% representing 1 p.u.
  - Configure the GFM inverter and diesel with the same droop settings:
    - Frequency: 0.6%,
    - Voltage: 6%.
  - Equal power sharing (baseline)
  - Unequal power sharing.

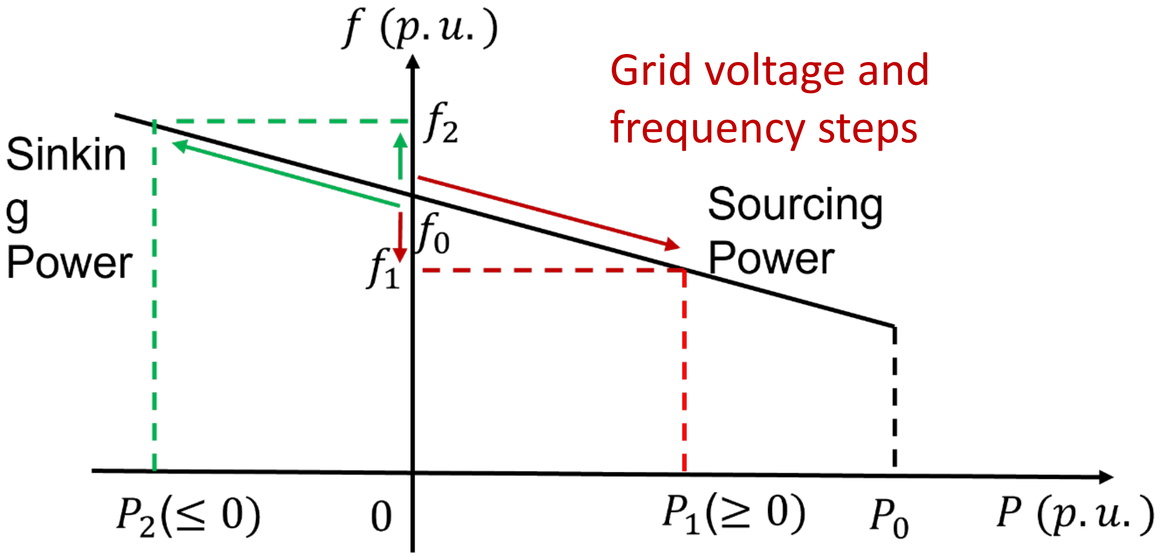


Testing Configuration

- Grid-connected operation
  - For active power, it is a balance game between the grid frequency and the inverter voltage:
    - $f_{grid} = f_{Inv}$, no power flow
    - $f_{grid} > f_{Inv}$, active power flows from the grid to the inverter
    - $f_{grid} < f_{Inv}$, active power flows from the inverter to the grid
  - The same for the reactive power output.



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



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

f_1 and f_2 are grid simulator stepped frequency

Testing Configuration

- <u>Transition operation:</u>
  - Key for smooth microgrid transition operation: **Minimize the PCC power flow** and **maintain the same operating point before and after the transition operation.**

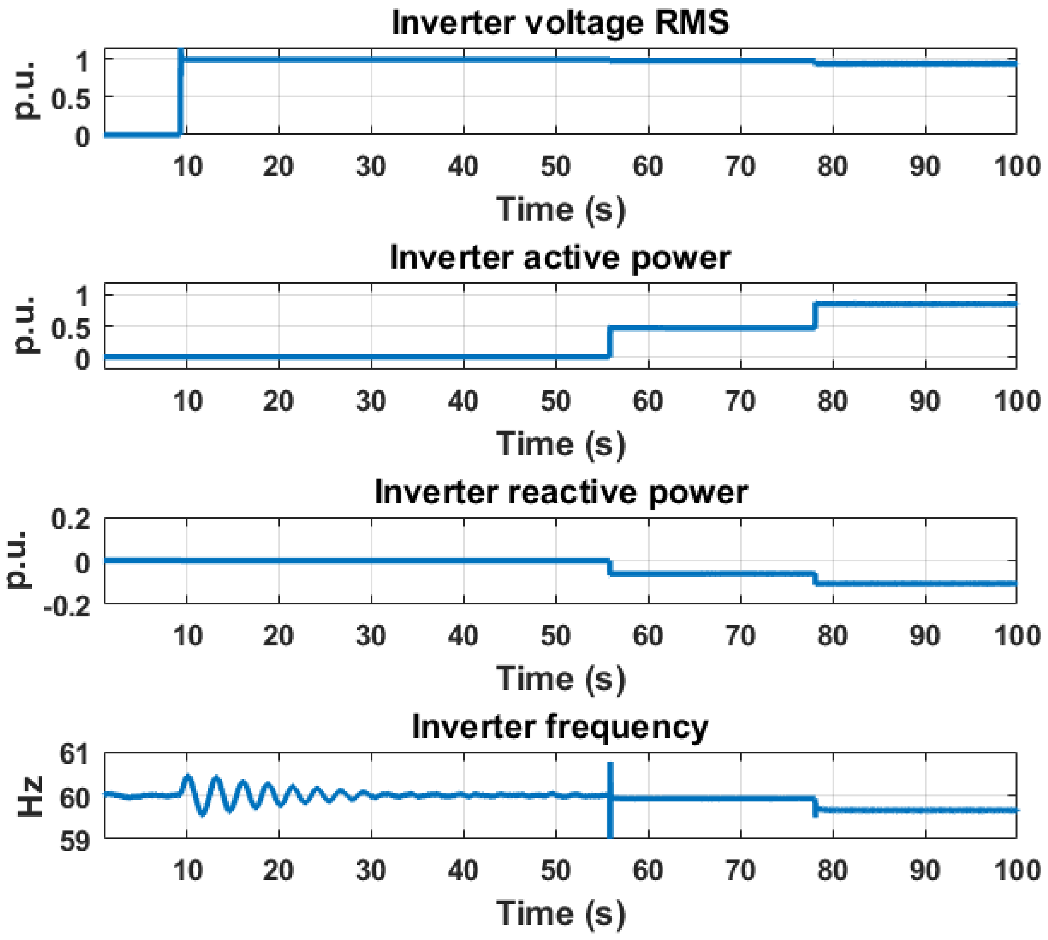
Loading (50%)	Islanded	Synchronization <u>Key strategy</u>: PCC power flow is minimized and inverter maintains the same operating point (v, I, P, Q, f)	Grid-connected	Islanding (same strategy as synchronization operation)
PF=1	Inverter with load	Before CB is closed, shift the frequency droop up by Δf=0.006*0.5*60=0.18 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

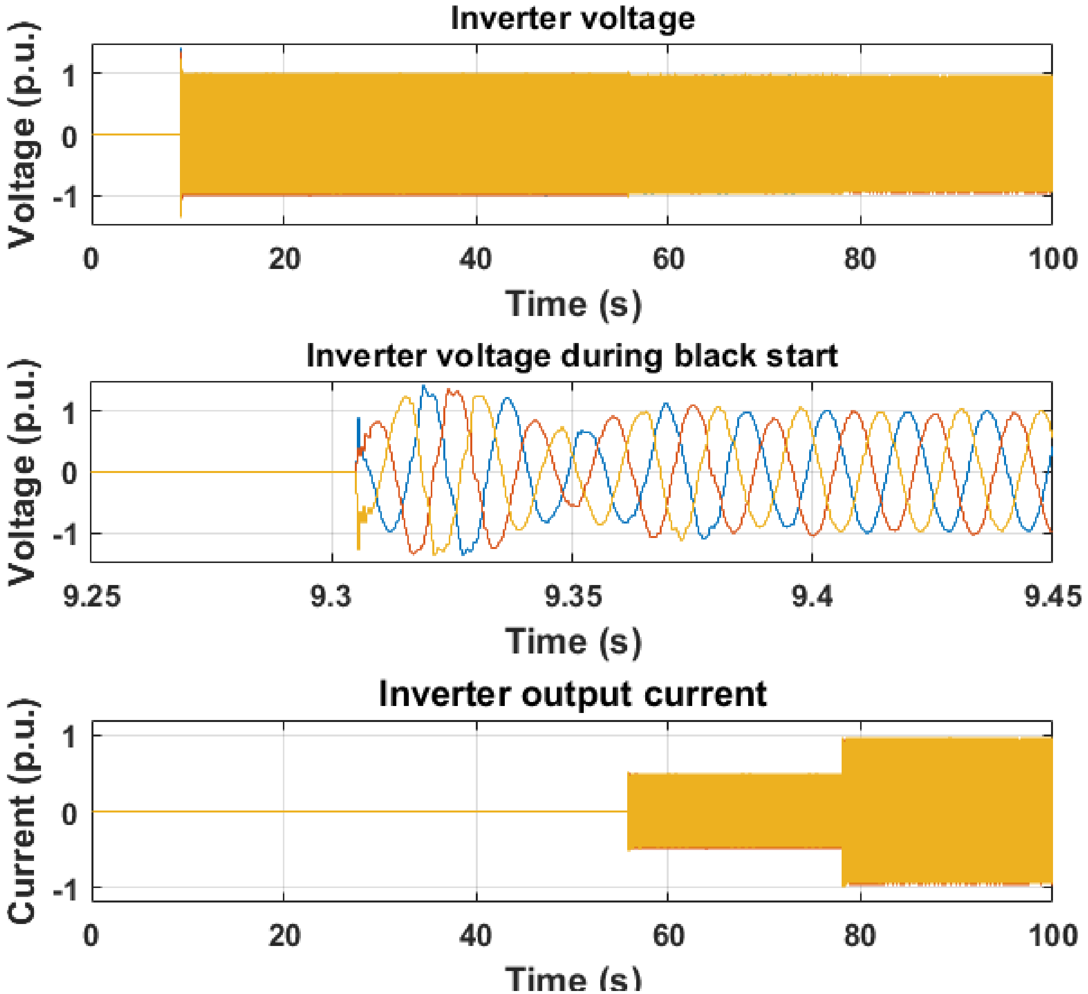
EXPERIMENTAL RESULTS—STAND-ALONE

- **Balanced load:**
  - The inverter can operate within the full spectrum of its active and reactive power.
  - THD of V and I are mostly below 5% except capacitive load (5% and 10%).
  - Inverter voltage drops below 0.95 p.u. at 100% loading.
  - There is a strong coupling between voltage and active power.
- **Unbalanced load:**
  - Inject negative sequence current.
  - Capable of handling all the unbalanced loading test
  - Voltage imbalance is below 0.25%.
- **Sinking power:**
  - Able to absorb the excessive active and reactive power from the GFL inverter.
- **Load step:**
  - Can handle all the load steps.
- **Overloading:**
  - Can handle all the overloading except PF 0.8 lagging and leading from 1.6 p.u.
  - Duration: 5~9 seconds.

Experimental Results—Stand-Alone

Black start: Energize transformer → 50% load → 100% load.

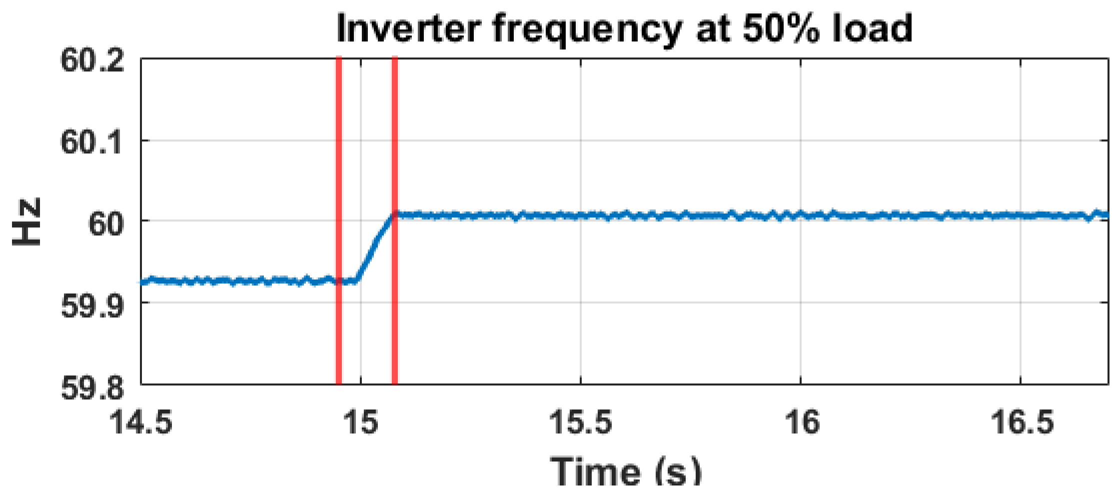


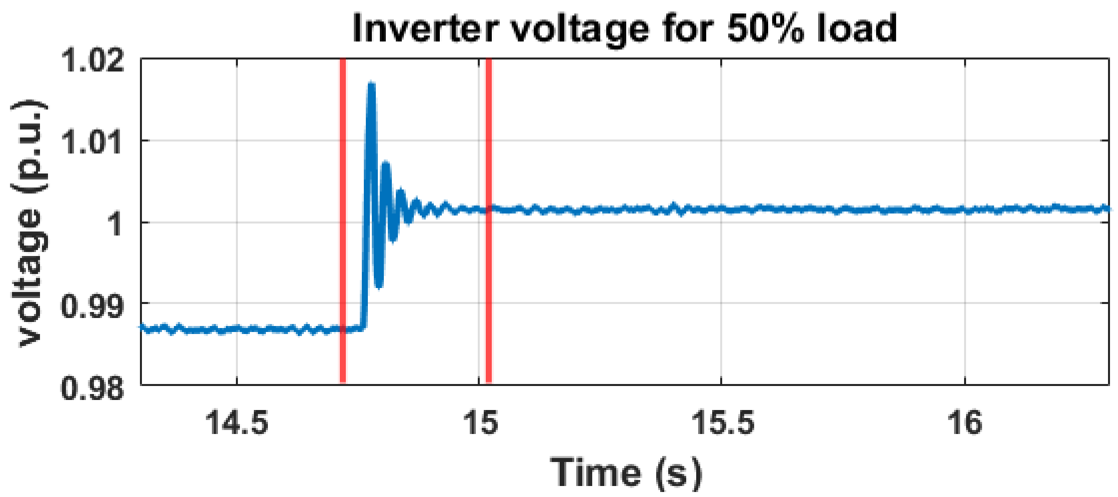


EXPERIMENTAL RESULTS—STAND-ALONE

Secondary control: 50% PF=1 load applied

- Frequency: smoothly regulated to the nominal value with 0.25 s
- Voltage: Exhibits oscillations and reaches steady state within 0.5 s.

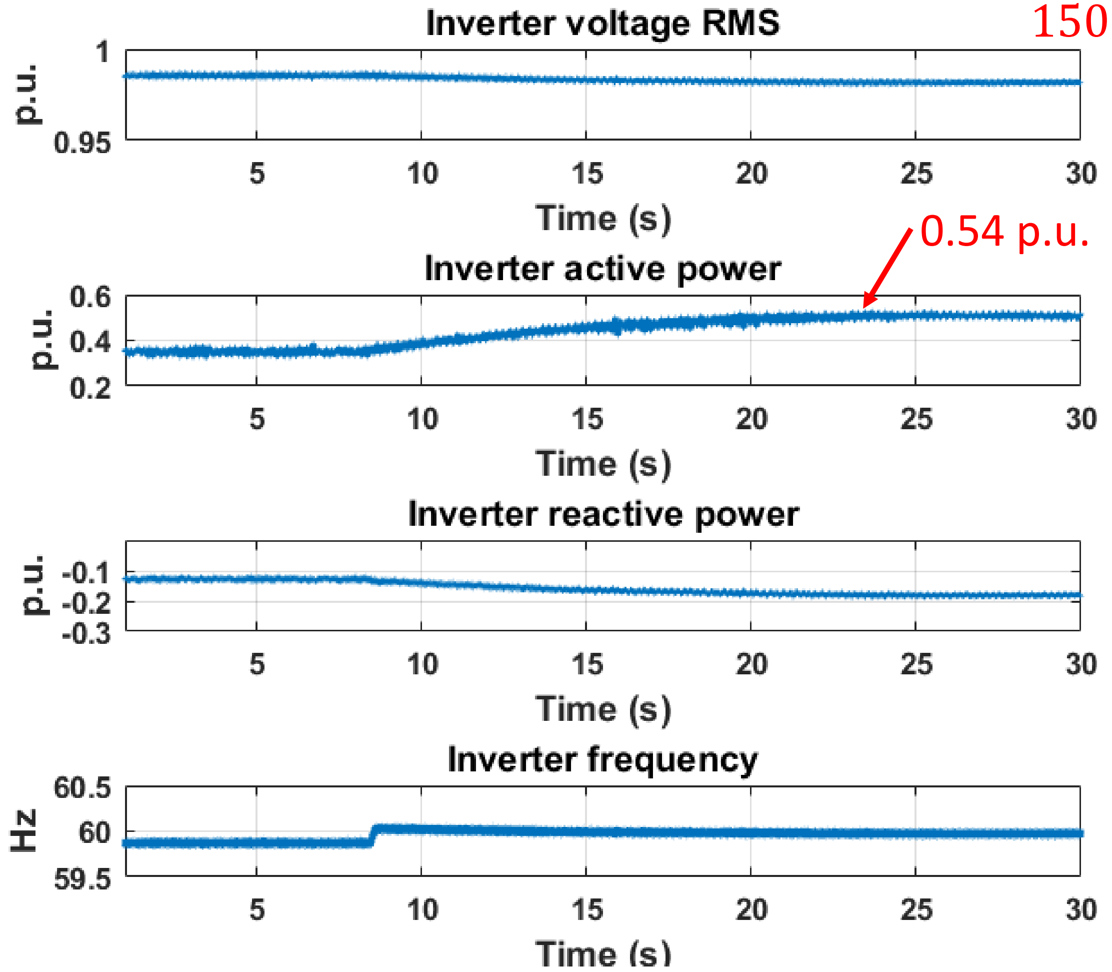


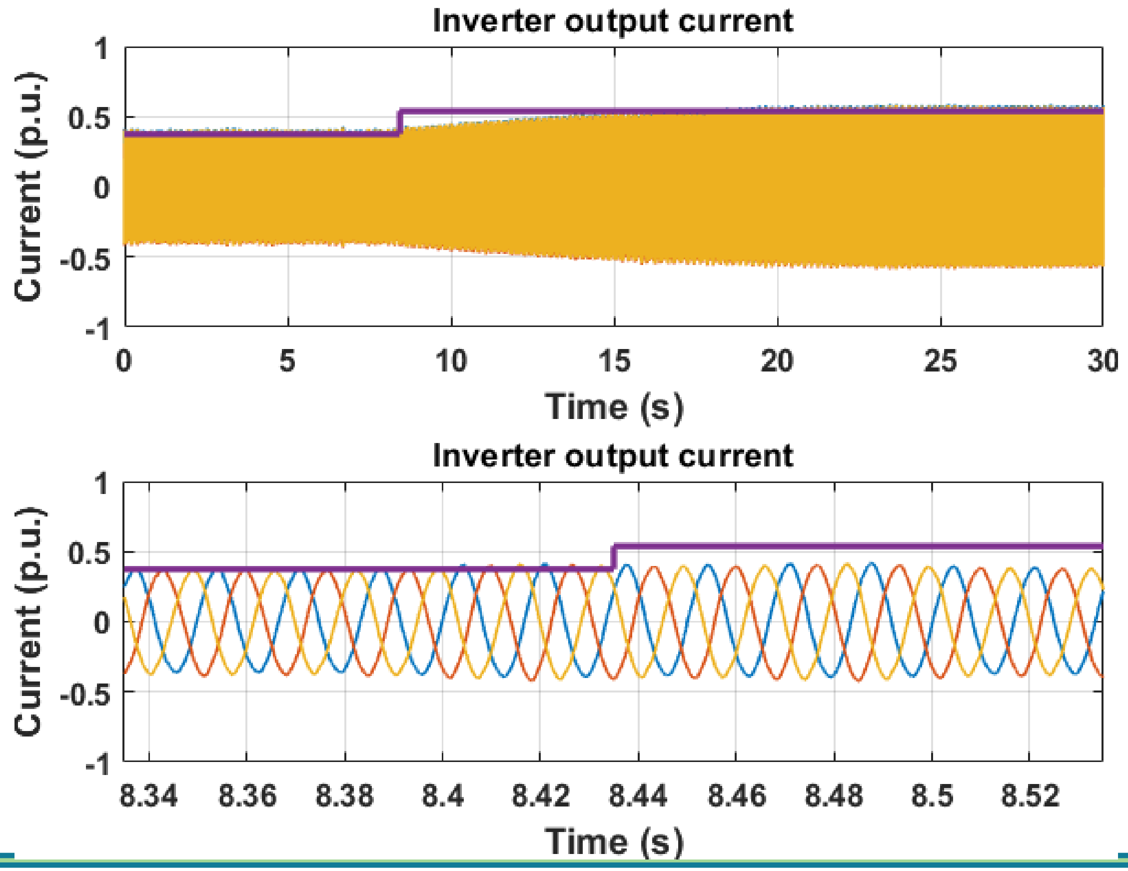


Experimental Results—Heterogeneous

Unequal power sharing: Start from equal power sharing → take 90% of the load.

$$\frac{150}{150+250} = 37.5\%. \qquad 0.9 * \frac{150}{250} = 0.54$$



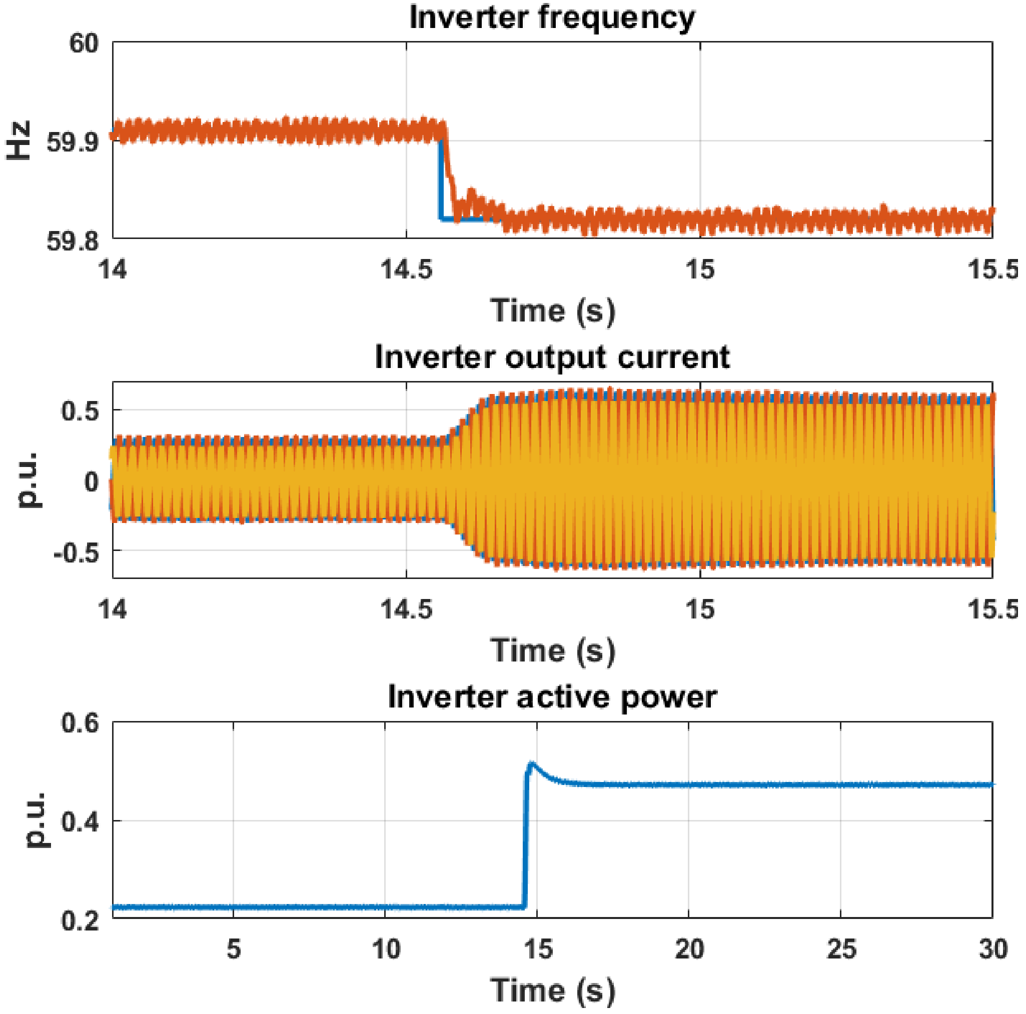


Experimental Results—Grid-Connected

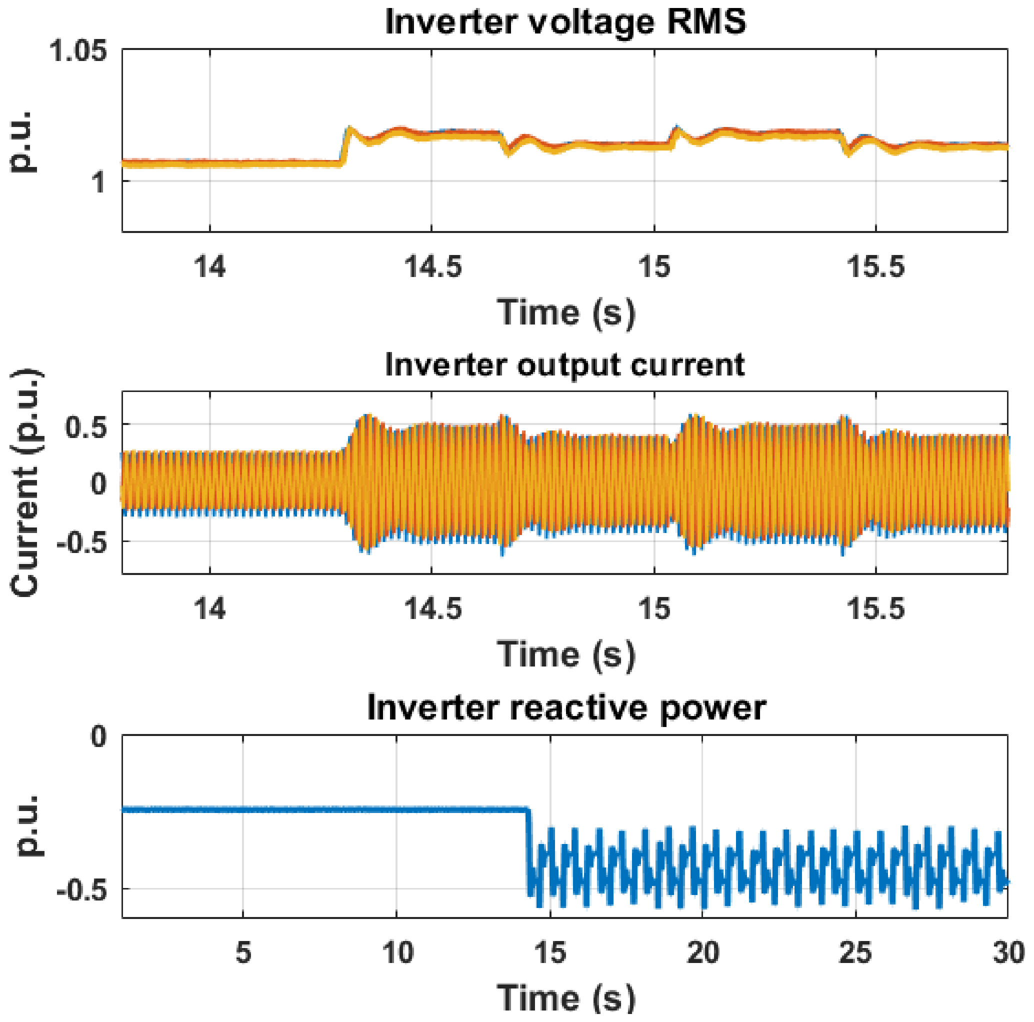
- Sourcing active power:
  - There is noisy current when the frequency droop is not shifted.
  - Inverter outputs the target active power except the 100% (derating effect).
  - Voltage THD is below 0.5% and current THD is high with low power (5% and 10%).
  - No overshot in the output current.
  - Inverter absorbs reactive power and increases when the loading is increased.
- Sourcing reactive power:
  - Outputs the reactive power slightly lower than expected
  - Voltage THD is below 0.5% and current THD are all above 5%
  - Inverter output current shows overshoots and settles within 1 s .
- Sinking active power:
  - Can complete all the testing
  - Inverter absorbs the target active power
  - No oscillations
  - Inverter absorbs slightly higher power than expected
  - Voltage THD is below 0.5% and current THD is above 5% from 5% to 50%.

Experimental Results—Grid-Connected

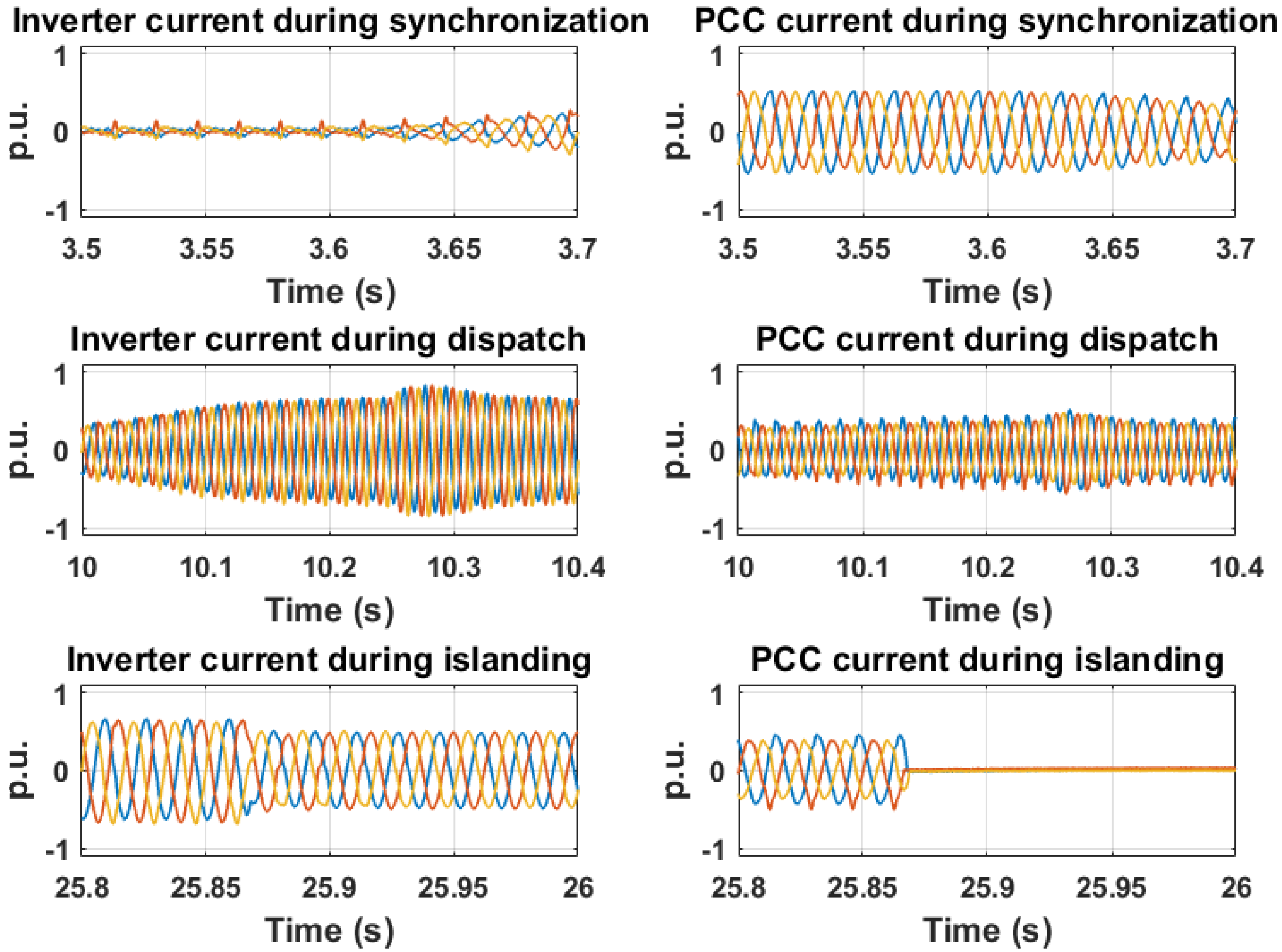
Grid simulator step-down frequency

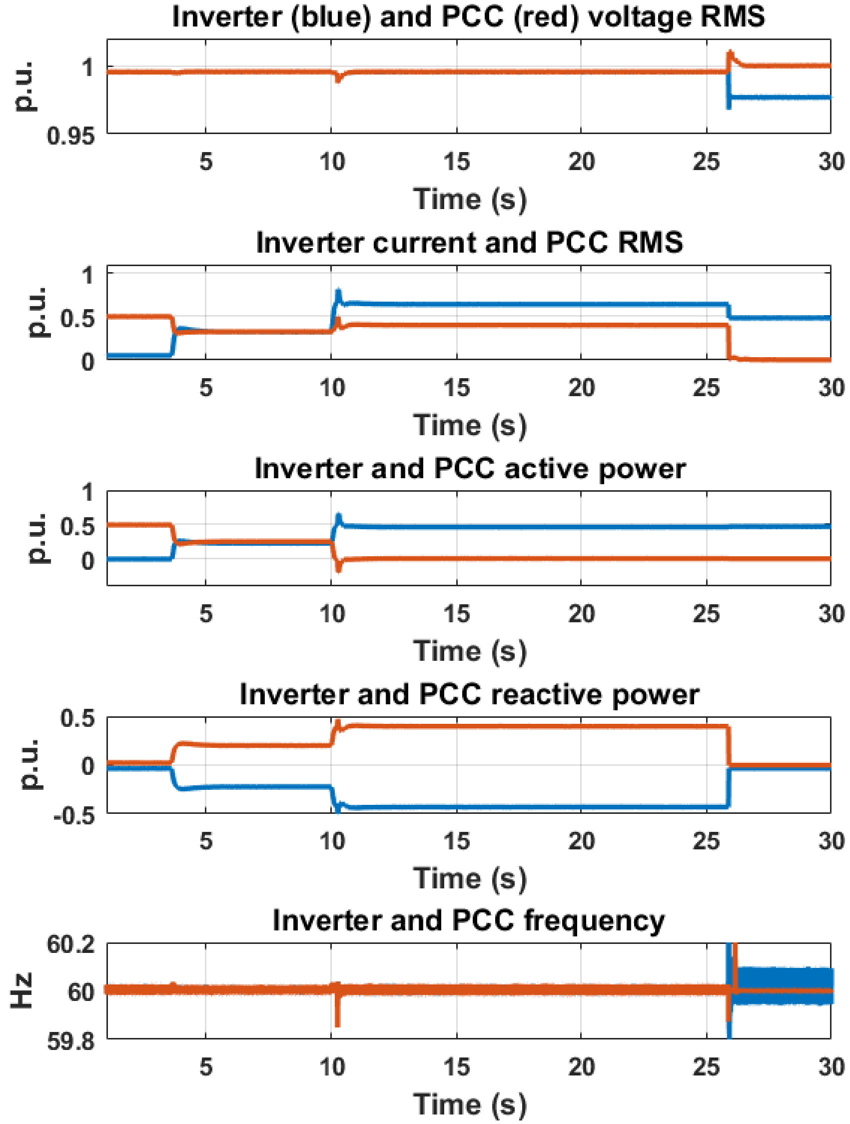


Grid simulator step-up voltage



Experimental Results—Transition Operation (PF=1 50% load)





CONCLUSION

- Develop a testing protocol to perform extensive lab testing of GFM inverter.
  - Understand the control functionalities and interoperability.
- The frequency and voltage droop need to be characterized.
- Tuning the droop slope can easily cause stability issues.
- We can perform secondary control and dispatch GFM inverters like GFL inverters through adjusting the droop intercept.
- Reactive power sharing is a problem.
- More studies are needed for grid-connected operation, especially for reactive power dispatch.

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

Acknowledgement and Disclaimer

Acknowledgement

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