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Performance Evaluation of a Single-Phase Grid-Forming Inverter Through Hardware Experiments

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Background and Motivation

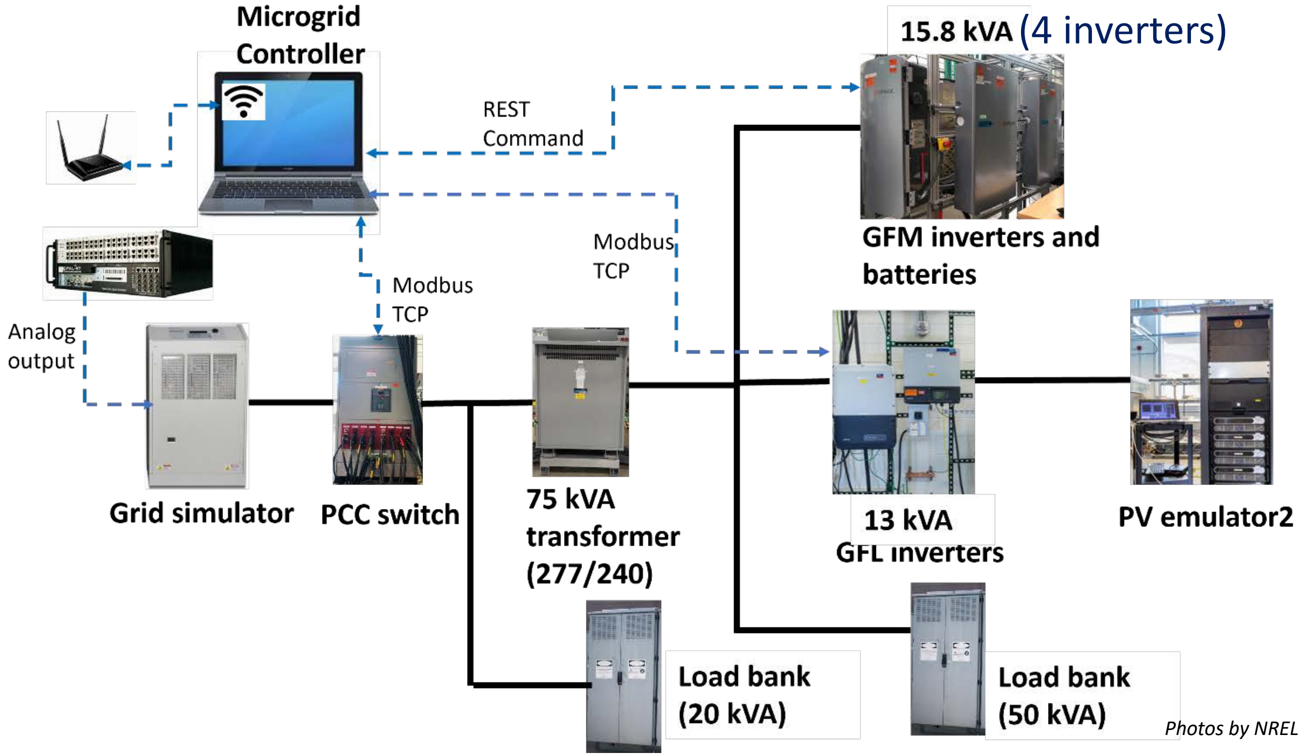
- There is a lack of standard testing protocols for single-phase grid-forming (GFM) inverters.
    - Develop standard testing protocols to understand the performance of single-phase GFM inverters.
- Explore the interoperability and functionalities of single-phase GFM inverters.
    - Test the key operation functions and modes of single-phase GFM inverters.
- Provide findings and guidelines for the inverter vendor.
    - What is the overall performance of the inverter?
    - What can be improved and how?

THE CHARACTERIZATION TEST

Testing objective:

- ✓ Investigate the steady-state and transient performance of the inverter.
- ✓ PQ capability, dispatchability, overloading capability, step response, black-start capability, and smooth transition operation
- ✓ Dynamic response under grid events, output impedance characteristics and damping ratio, and inertia response.

The Test Circuit

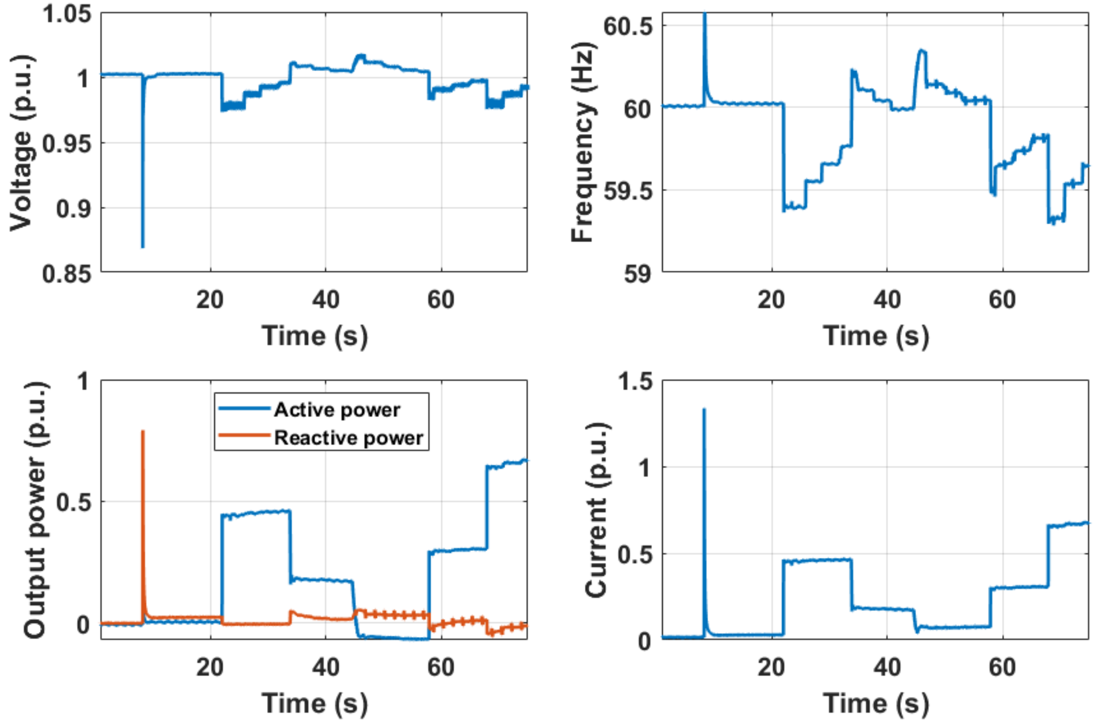


- Always GFM control
- No droop
- Dispatch P only through REST command.

Configuration	Test Type	Scenarios	Test approach
Stand-alone	Steady state	Single-phase load	Power factor (PF) 1, PF 0.8 lagging and leading, representing 5%, 10%, 25%, 50%, 75%, and 100% loading of the inverter capacity
		Sinking power	The inverter operates in parallel with a grid-following (GFL) inverter that is supplying more power than the available load on the islanded power system.
	Transient	Black start	Starting from OFF, the inverter must energize a transformer of similar kVA size and connect the load(s) and GFL inverter(s) based on the predefined sequence.
		Load step	PF of 1, 0.8 lagging, and 0.8 leading. The load steps will be performed from 0% to 50%, 50% to 100%, and 0% to 100% of the inverter kVA rating.
		Overload	The inverter will be subjected to 150% overcurrent at power factors of 1 and 0.8 lagging and leading. This will be held for x seconds until the inverter trips.
		Loss of generator	The GFL inverter(s) is intentionally tripped off so that the GFM inverter will take over all the load and survive the islanded system.
Grid-connected	Steady state	Sourcing & sinking power	The inverter frequency droop intercept is adjusted to force the inverter to source/sink 5%, 10%, 25%, 50%, 75%, and 100% rated kW/kVar.
		Impedance scan	No load is connected, and the inverter is dispatched to inject 50% active power. The harmonic voltage perturbation is 1% with frequency sweeps from 3, 5, 7, 9, up to 1957 Hz.
	Transient	Dynamic event	The voltage jumps up/down by 0.01, 0.02, 0.03, 0.04, and 0.05 p.u., and the phase jumps up/down by 5°, 10°, 15°, 20°, and 30°.
		Inertia response test (ROCOF)	PF=1 load with 50% capacity of the GFM inverter, and the GFM inverter is dispatched by injecting 0% power. The grid frequency will be changed with a rate of change of frequency (ROCOF) of 1 Hz/s at zero power or light loading (e.g., 20%).
Transition operation	Transient	Synchronization and islanding	The inverter energizes a local power system and connects to a larger grid, and then it performs the planned islanding operation.

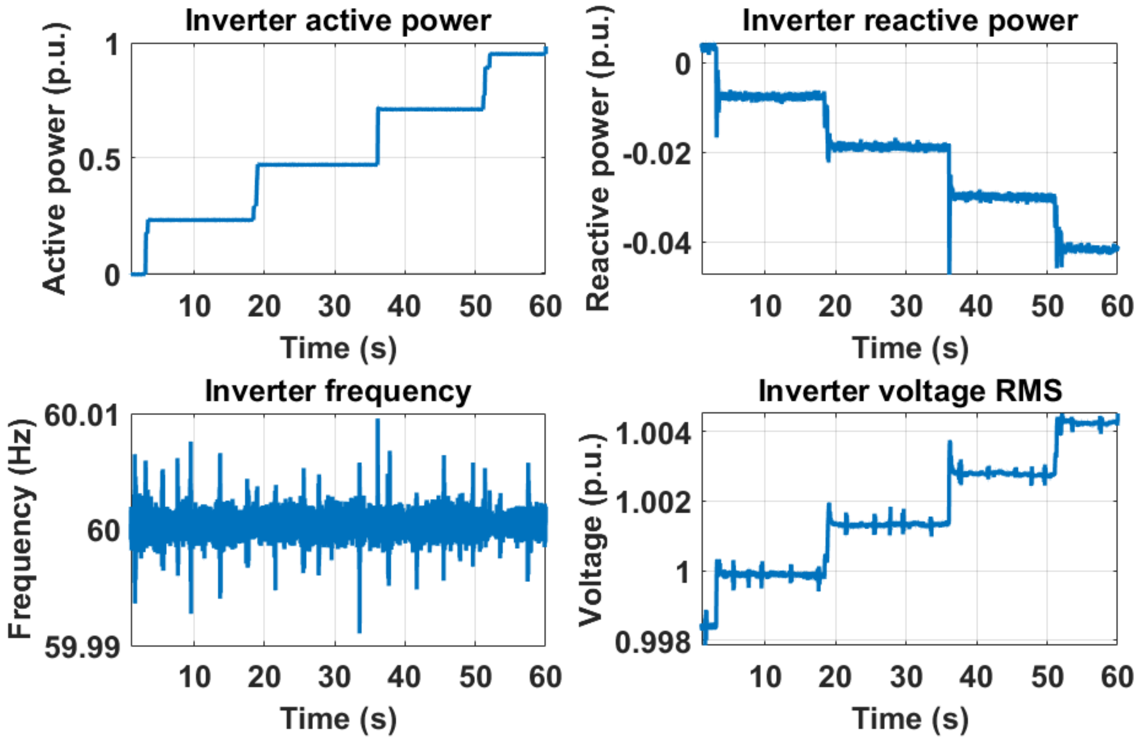
EXPERIMENTAL RESULTS

Black Start



- Black-start test is successful.
- First spike is from energizing the transformer 240/277 V.
- Voltage and current THD are below 2% and 5%, respectively.

Sourcing Power



- Follows the active power set points very well.
- Only active power dispatch is allowed.
- Frequency is maintained around 60 Hz, and voltage slightly increases.

EXPERIMENTAL RESULTS

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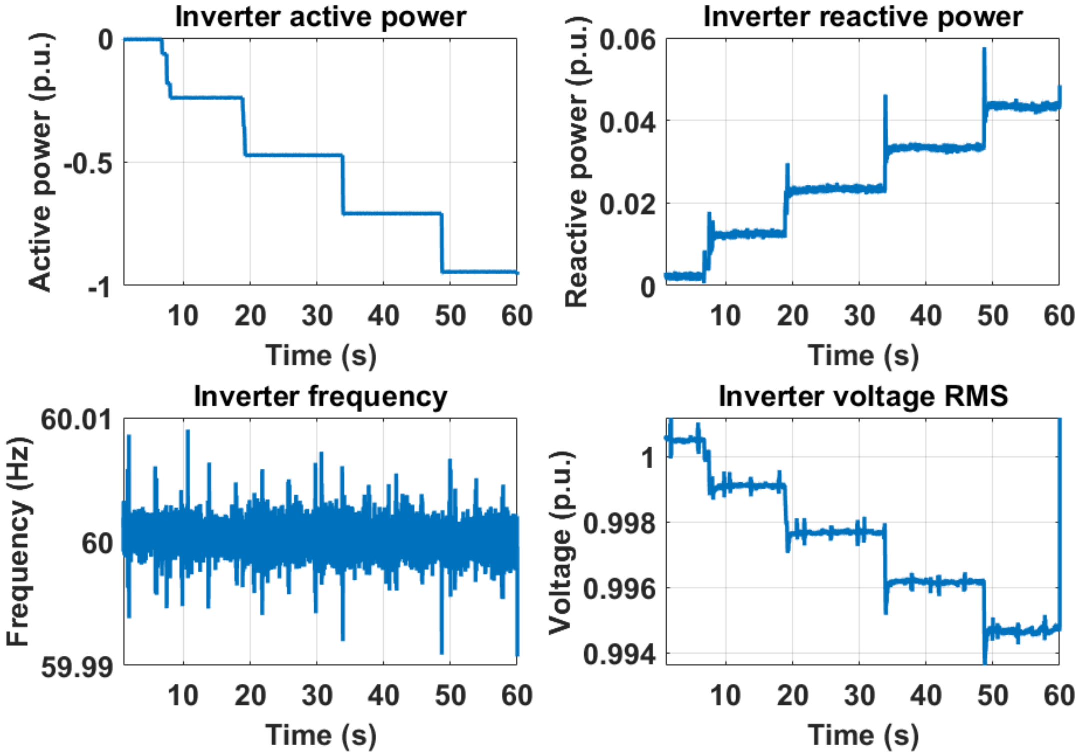
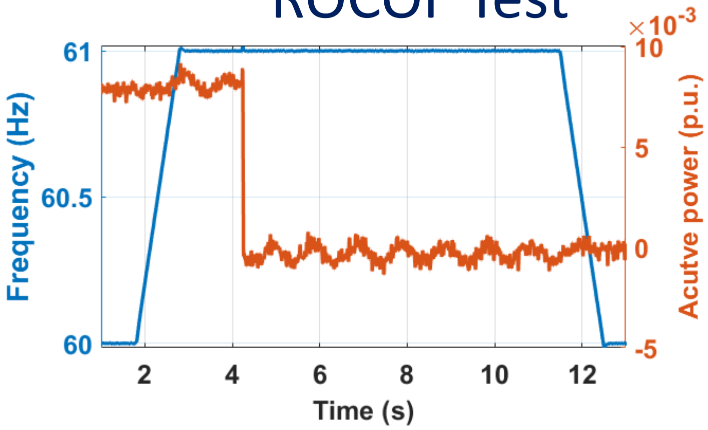
Sinking Power



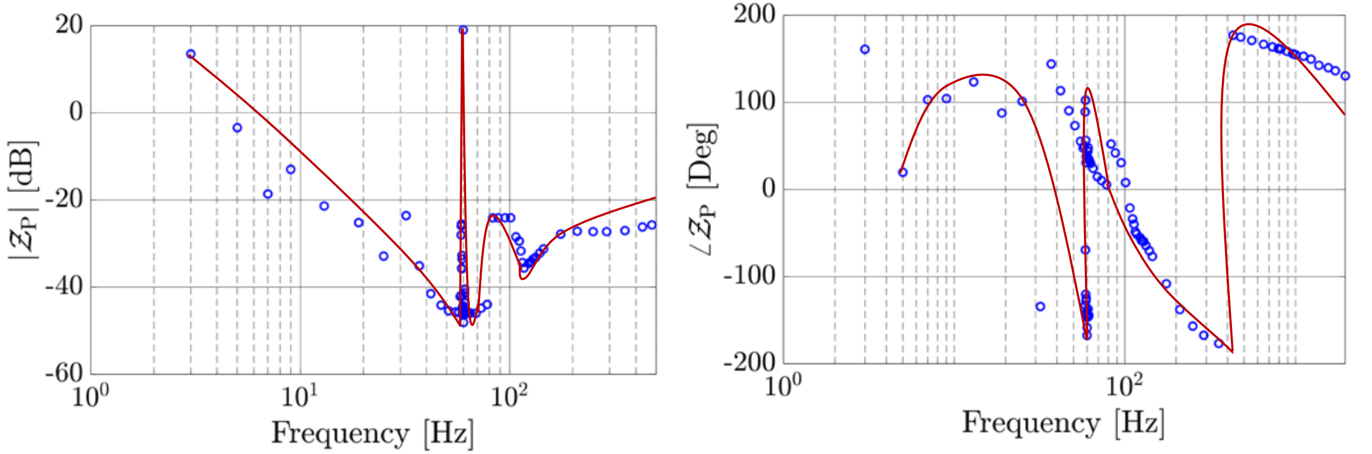
- Follows the active power set points very well.
- Frequency is maintained around 60 Hz, and voltage slightly decreases.

ROCOF Test



- Active power does not respond to frequency change.
- ROCOF test failed!

Impedance Scan Test

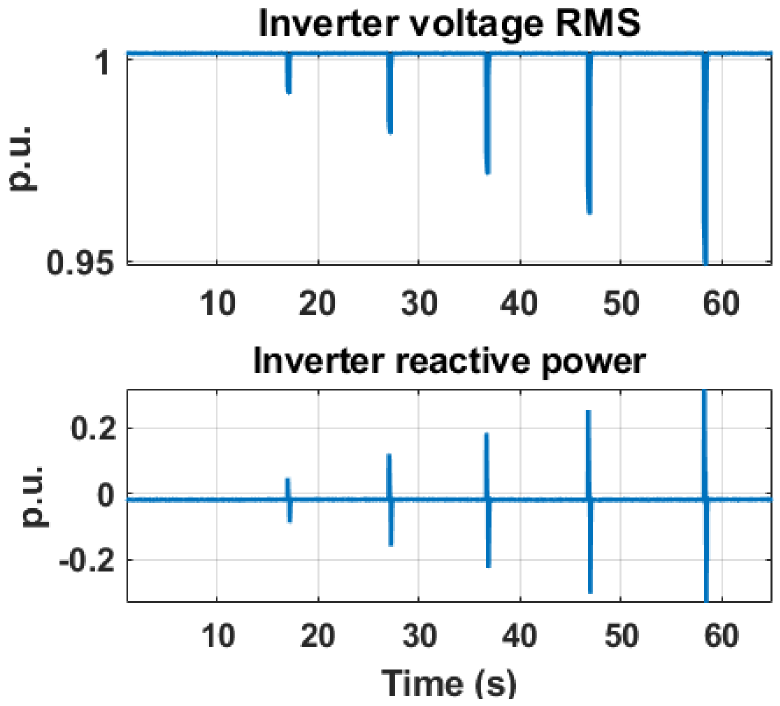


DuT	Non-piece-wise Transfer Function	FitPercent
GFM-1	$\frac{0.712(s+1.6\times10^4)(s+3521)(s-250)(s-134.8)(s^2+3.29s+1.525\times10^8)}{(s^2+\mathbf{249.9}s+1.432\times10^5)(s^2+870.7s+1.32\times10^8)(s^2+3.59s+1.5\times10^8)}$	96.87%

DuT	Damping
GFM-1	$\zeta_{est}^{dut} \approx 0.33$

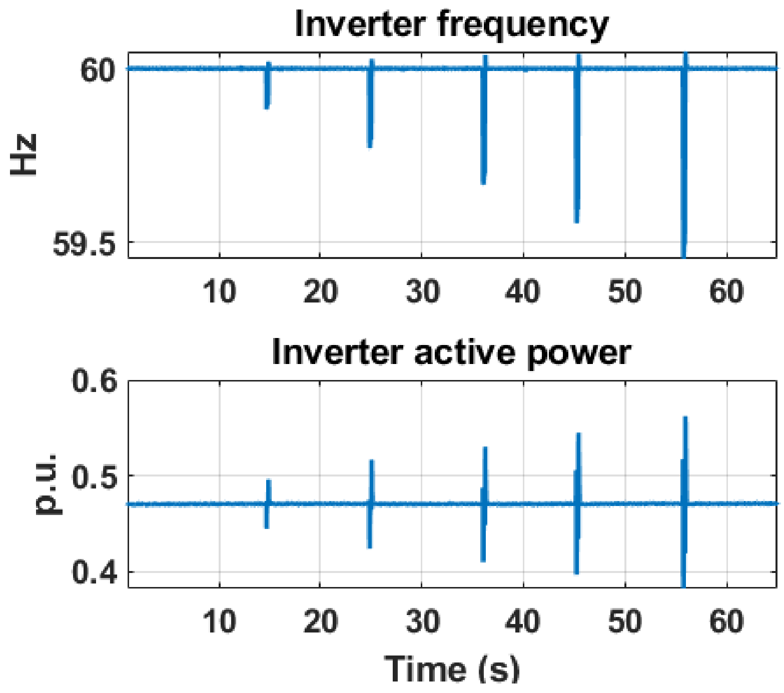
Experimental Results

Voltage Jump Down



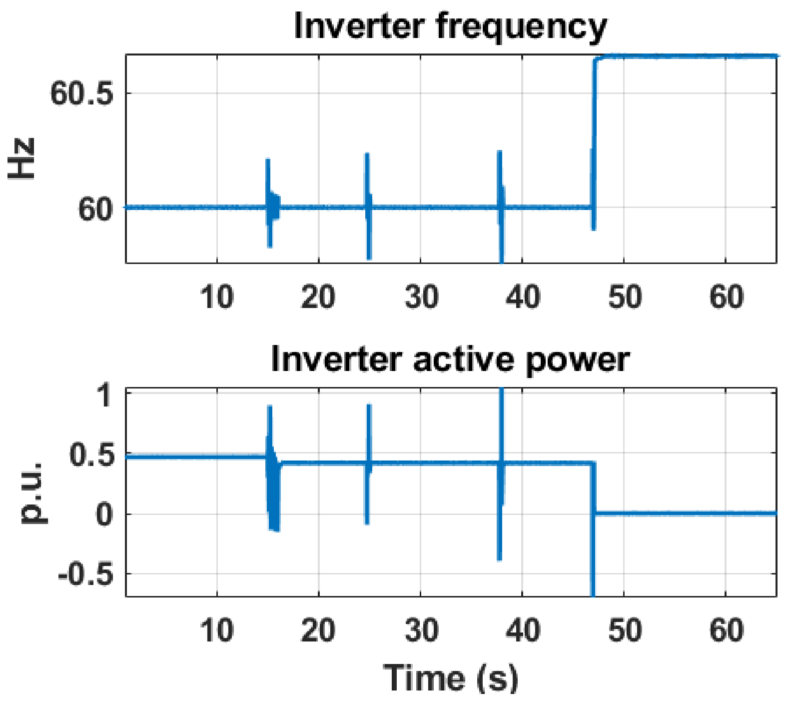
- Reactive power responds correctly to the voltage dip.

Frequency Jump Down



- Active power doesn’t respond correctly to the frequency jump down.

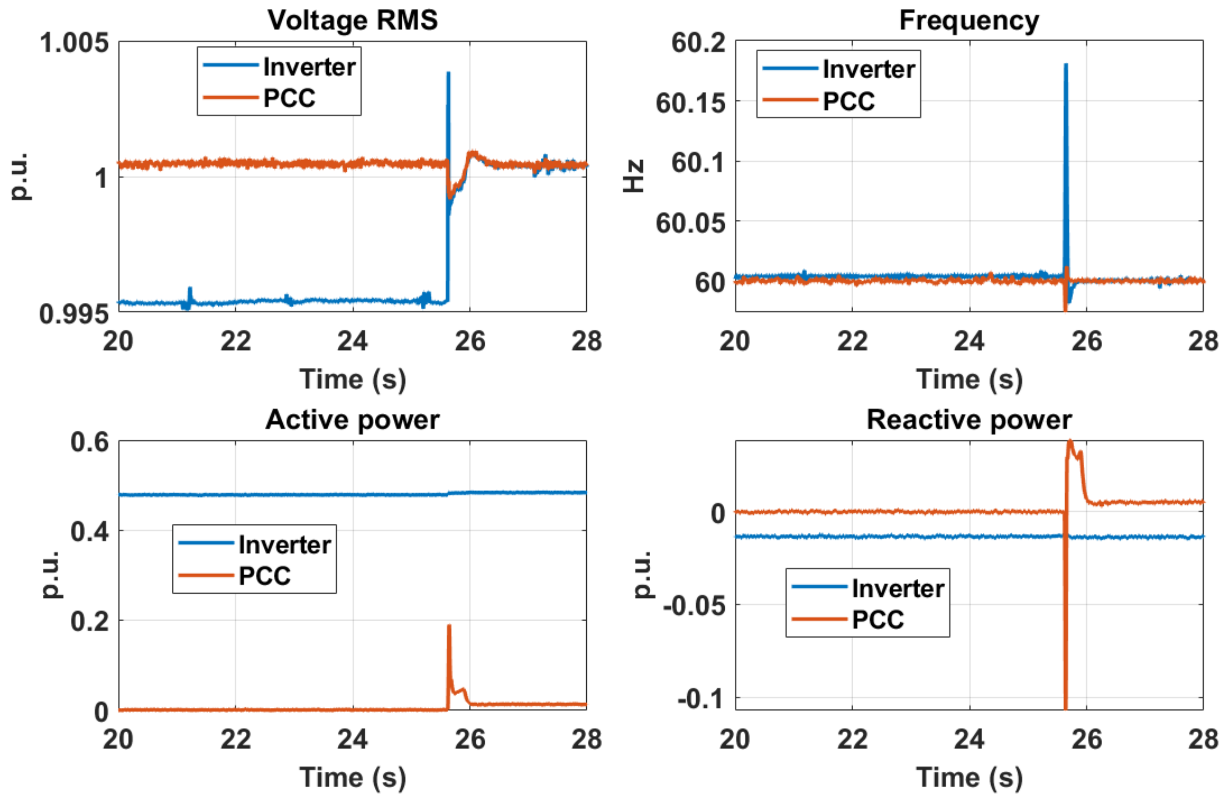
Phase Jump Up



- Unexpected oscillations in active power
- Active power responds correctly.
- Inverter tripped at the last test.

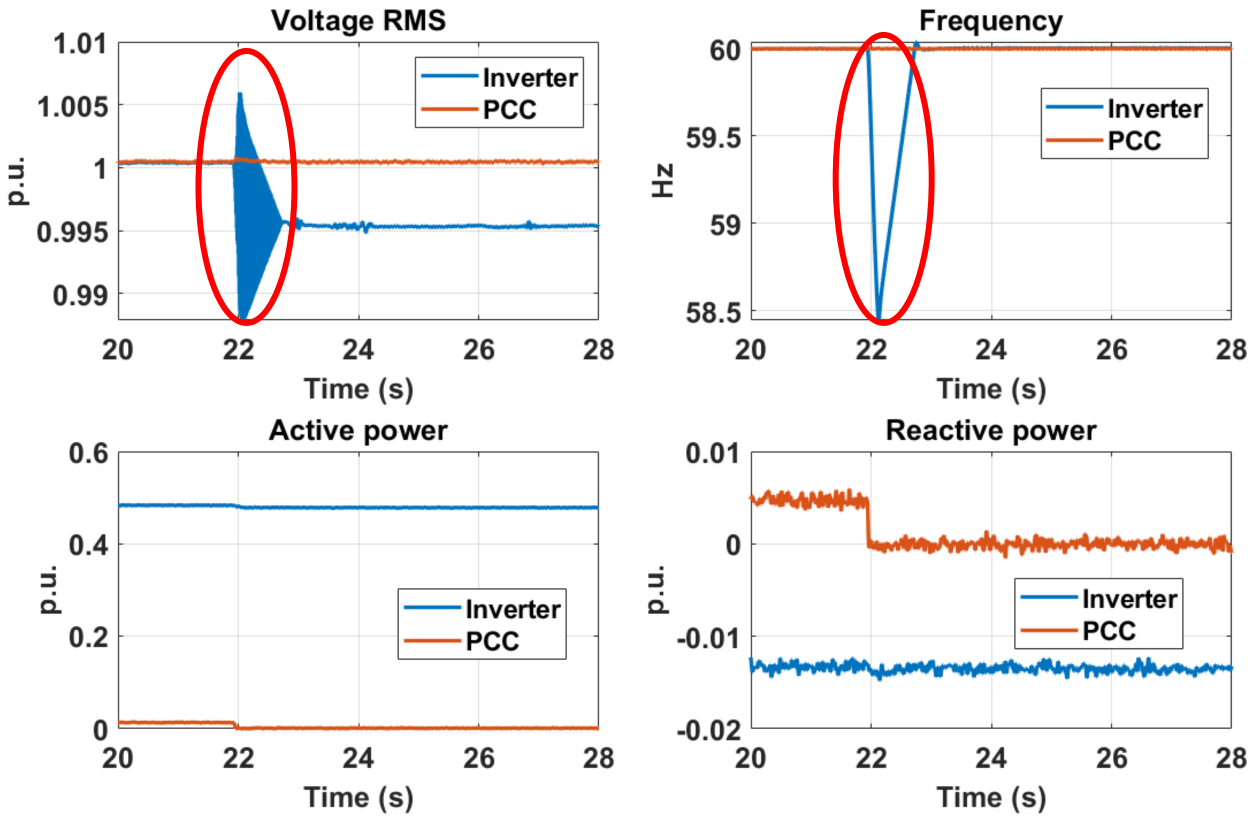
EXPERIMENTAL RESULTS

Synchronization Operation



- Successful synchronization operation with small transients.

Islanding Operation



- Successful synchronization operation but with noticeable and unexpected transients.

CONCLUSION

- The performance and functionality of the single-phase GFM inverter is evaluated based on a variety of scenarios and performance metrics.
  - Serves as standard performance test protocol to address the gap.
- The performance of this single-phase inverter is satisfactory.
  - It is capable of being the islanding master for homes when the main grid is gone.
  - This single-phase GFM inverter can be used as a GFM source to support local resiliency.
- Things to improve:
  - Grid support function needs to be improved (voltage, frequency, and phase jump).
  - Suggest enabling droop control rather than only isochronous.
  - The islanding operating can be enhanced by maintaining the same operating points before and after the breaker is open.

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Thank you!

Photos by NREL

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