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Grid-Forming and Grid-Following Inverter Comparison of Droop Response

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Introduction

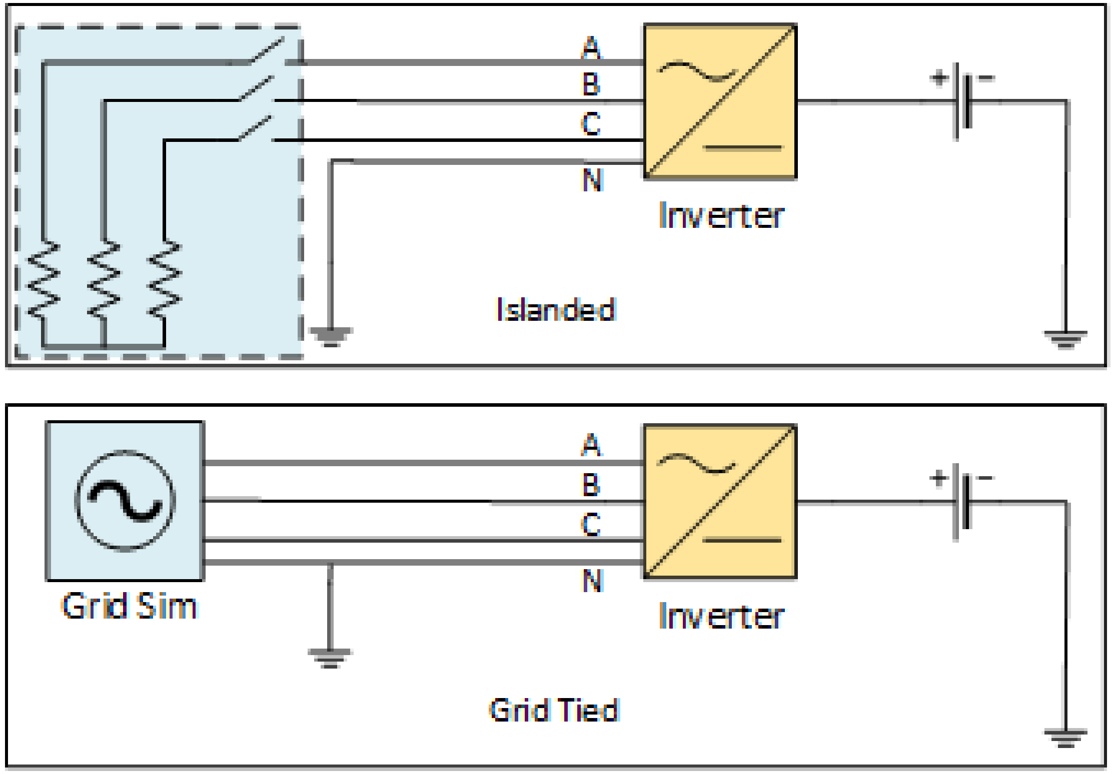
- Renewable energy resources are becoming more prevalent
  - These resources are commonly inverter based (IBRs)
- Grid-following inverters (GFLIs) do not provide real or emulated inertia
  - Commonly used for Photovoltaic (PV) systems
  - Other means are required to help grid stability
- Modern grid interconnection standards look to fix this
  - Grid support functionalities (GSFs) are common on more recent inverters
- Grid-forming inverters (GFMIs) commonly use a form of droop control for load sharing and paralleling to primary sources
  - Droop characteristics are similar to GSFs such as volt-var (VV) and frequency-watt (FW) in response to deviations in voltage reference

Background

- IEEE Std 1547-2003 created following influx of PV systems
  - No GSFs, no voltage or frequency ride throughs
  - Inverters tripped when outside of normal operating conditions
  - Minimal acceptance of IBRs on the utility
- IBRs started to become more prevalent, especially in California
  - Couldn't wait for 1547 to be revised, CA took initiative
  - CA Rule 21 revised
  - Requirement of VV functionality, w/ reactive power priority
  - FW was optional
- IEEE Std 1547-2018 addressed needs for additional GSFs
  - Includes VV, FW, watt-var and volt-watt
  - Indication of growing acceptance for distribution level IBRs as a capability
- GFMIs with droop capability and potential for providing emulated inertia are viable replacement for synchronous machines.

Experimental Setup

- Equipment Under Test
  - 100kW GFMI (energy storage inverter w/ Virtual Synchronous Machine (VSM) control)
  - 24kW GFLI (PV inverter)
- DC Sources
  - NH Research 9300 100kW Battery Emulator
  - Ametek TerraSAS 100kW PV Simulator
- Grid Tied Testing
  - Ametek RS-90 Regenerative Grid Emulator
- Islanded Testing
  - 0-150kW delta configuration resistive load
  - 0-150kVar delta configuration inductive load



GFLI Frequency Response

- Inverter Settings
  - Most aggressive FW profile according to 1547-2018
  - Open loop response times set to 0.0, 0.2, 1.0, 5.0, and 10.0 s
- Grid Emulator Settings
  - Voltage held at 277/480 V
  - Frequency changed from 60 to 61 Hz
  - Rate of Change of Frequency (ROCOF) of 3 Hz/s used for all OLRT
  - 10 and 100 Hz/s tested at 0.0 s OLRT
- Results
  - Response time of around 7.3 s when set to 10.0 s OLRT
    - Slow ROCOF should not have affect on response time
  - Fastest response of around 500 ms seen with 0.0s OLRT at 10Hz/s
    - Response time limitation probably due to interference between rapid change and Phase-Locked Loop control used in GFLIs

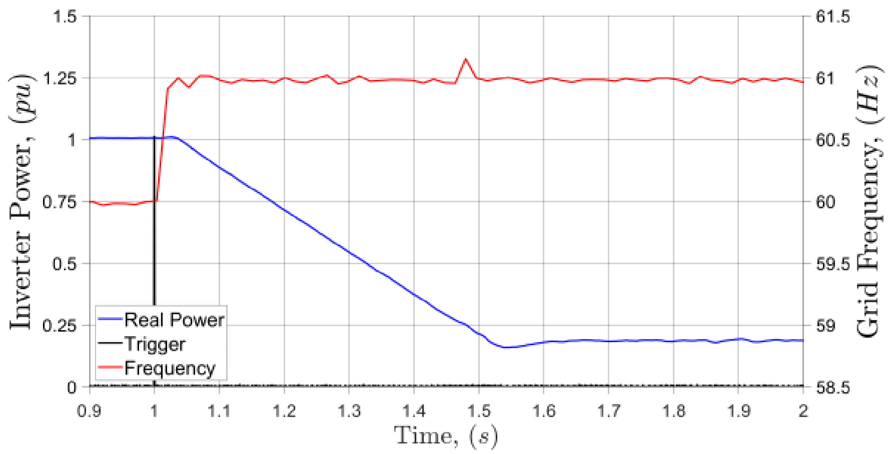


Fig. 2: GFLI Frequency Response, 100 Hz/s Ramp to 61 Hz

GFLI Voltage Response

- Inverter Settings
  - Most aggressive VV profile according to 1547-2018
  - Open loop response times set to 2.0, 5.0, and 10.0 s
- Grid Emulator Settings
  - Frequency held at 60 Hz
  - Voltage changed by ±2.0% of V_{nom} (277/480 V) in 1 ms
- Results
  - At 10.0 s OLRT, a response time of around 12.3 s was seen in the negative voltage change direction, and around 10.3 s in the positive direction
    - Slower response in the negative direction is due to the inductance of the output filter
  - Approximately 3.1 s and 2.2 s response time seen for the 2.0 s OLRT in the negative and positive directions respectively
    - EUT did not allow to set faster OLRT

TABLE II: GFLI VOLT-VAR RESPONSE TIME

Open Loop Response Time:	Voltage Setpoint (p.u.):	Settled Power (p.u.):	Power Response, 1% (s):	Response Time Error (%):
10.0s	0.98	0.4373	12.347	23.5
	1.02	-0.4388	10.357	3.6
5.0s	0.98	0.4404	6.624	32.5
	1.02	-0.4388	5.233	4.7
2.0s	0.98	0.4387	3.106	55.3
	1.02	-0.4388	2.163	8.2

GFMI Grid-Tied Frequency Response

- Inverter Settings
  - 2% frequency droop set to match GFLI FW slope, voltage droop left at default 5%
  - Inertia time constant (ITC) kept at default 1000 ms
- Grid Emulator Settings
  - Voltage held at 277/480 V
  - Frequency changed to ±1% of F_{nom} (60 Hz)
  - ROCOF of 3, 10, and 100 Hz/s tested
- Results
  - Slowest response of approximately 820 ms seen on negative frequency change at 3 Hz/s
    - For each ROCOF, the slower response was always in the negative frequency direction
  - Fastest response of 670 ms at 100 Hz/s
    - GFMI w/ VSM control response similarly fast to GFLI

TABLE III: GFMI GRID-TIED FREQUENCY RESPONSE, DEFAULT INERTIA PARAMETERS, 2% DROOP

ROCOF:	Frequency Setpoint (Hz):	Settled Power (p.u.):	Power Response, 1% (s):
3Hz/s	59.4	0.5087	0.818
	60.6	-0.5436	0.777
10Hz/s	59.4	0.5084	0.687
	60.6	-0.5437	0.713
100Hz/s	59.4	0.5083	0.717
	60.6	-0.5431	0.670

GFMI Grid Tied Frequency Response Continued

- Additional Tests
  - Various ITC and droop setpoints used to slow down response
    - ITC set to 1000, 2000, 5000, and 10000 ms
    - Droop set to 2, 5, and 10%
  - Frequency was changed with grid emulator such that around 0.5 p.u. of real power would drawn from the GFMI
    - ROCOF of 100 Hz/s used to take response delay out of the equation
- Results
  - Minimal increase in response time with some abnormalities

TABLE IV: GFMI GRID-TIED FREQUENCY RESPONSE, VARIABLE DROOP, AND INERTIA TIME CONSTANT

Time Constant:	Droop (%):	Frequency Setpoint (Hz):	Settled Power (p.u.):	Power Response, 5% (s):	Power Response, 1% (s):
1000ms	2	59.4	0.4972	0.1771	0.6414
	5	58.5	0.4962	0.1100	0.5975
	10	57.0	0.4970	0.1046	0.5219
2000ms	2	59.4	0.4968	0.1738	0.6159
	5	58.5	0.4962	0.1364	0.5643
	10	57.0	0.4970	0.1415	0.5939
5000ms	2	59.4	0.4972	0.2375	0.8446
	5	58.5	0.4963	0.1806	0.6198
	10	57.0	0.4972	0.2350	0.7173
10000ms	2	59.4	0.4971	0.4223	1.2786
	5	58.5	0.4966	0.2152	0.8352
	10	57.0	0.4972	0.3933	0.8806

GFMI Islanded Frequency Response

- Inverter Settings
  - Droop set to match initial GFMI grid tied testing
  - Default ITC
  - Set to blackstart
- Load Settings
  - Delta configuration resistive load bank
  - Block load from 0 kW to 20, 40, and 60kW
- Results
  - For 20kW load response to 1% of settled power was 20 ms
  - Around 210 ms response to 1% of settled power for 60kW load

TABLE V: GFMI ISLANDED FREQUENCY RESPONSE, DEFAULT INERTIA PARAMETERS, 2% DROOP

Block Load:	Settled Frequency (Hz):	Power Response, 1% (s):	Settled Power (p.u.):
0.20p.u.	59.68	0.020	0.2040
0.40p.u.	58.45	0.152	0.3946
0.60p.u.	59.20	0.211	0.5847

GFMI Islanded Frequency Response Continued

- Additional Tests
  - Various ITC and droop setpoints used to slow down response
    - ITC set to 1000, 2000, 5000, 10000, and 30000 ms
    - Frequency droop set to 2, 5, and 10%
  - 50kW block load was used
- Results
  - Response time ranged from 60 ms to 2.3 s (without signs of instability)
    - Voltage overshoot seen following load onset on tests at high ITC
  - At 10000ms, power oscillation seen for 2% droop test until stabilizing after 4.8 s
    - At 30000 ms ITC and 2% droop, the GFMI never reached stability

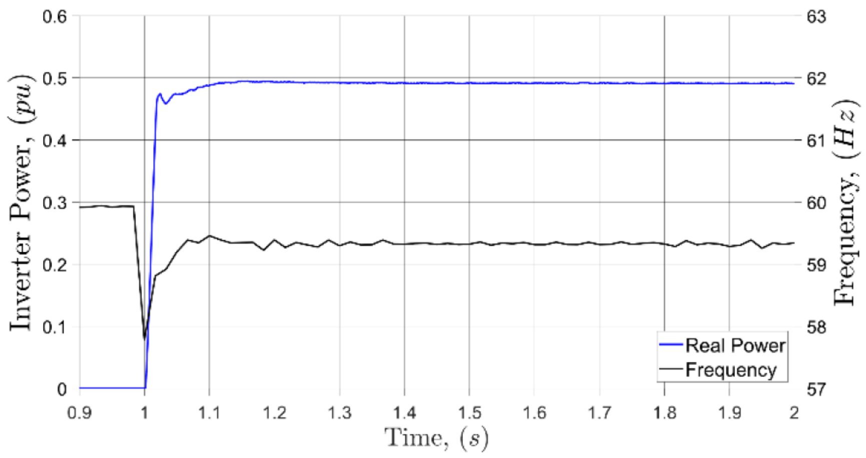


Fig. 3: GFMI, Islanded Frequency Response, 2% Droop, 1000 ms Inertia Time Constant

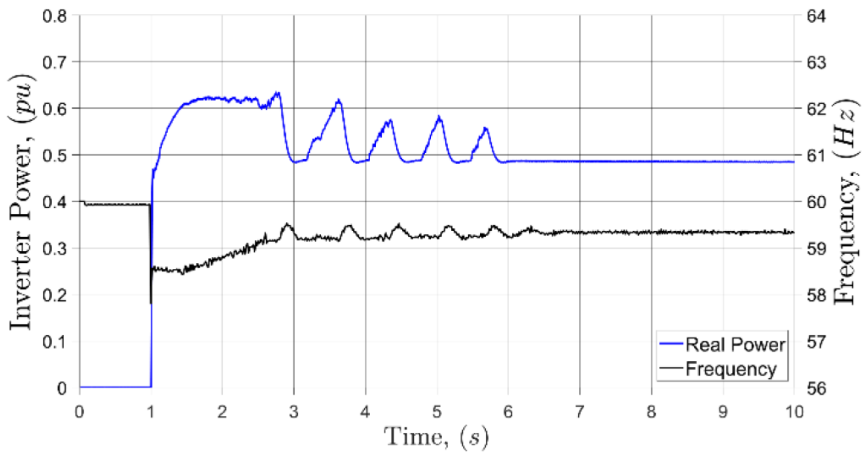


Fig. 4: GFMI Islanded Frequency Response, Initial Sign of Instability

GFMI Grid-Tied Voltage Response

- Inverter Settings
  - 1% and 5% selected for testing
  - ITC of 1000, 2000, and 5000 ms tested
- Grid Emulator Settings
  - Frequency held at 60 Hz
  - Voltage changed by ±2.5% of V_{nom} (277/480 V) for 1% droop and ±5.0% of V_{nom} (277/480 V) for 1% droop
    - These changes in voltage resulted in around 0.50 p.u. reactive power
- Results
  - Little variability seen between ITCs

TABLE VII: GFMI GRID-TIED VOLTAGE RESPONSE, VARIABLE DROOP AND INERTIA TIME CONSTANT

Time Constant:	Droop (%):	Voltage Set Point (p.u.):	Settled Power (p.u.):	Power Response (5%):	Power Response (1%):
1000 ms	1%	0.975	0.4622	1.3257	1.9909
	1%	1.025	-0.5109	1.7232	2.7462
	5%	0.95	0.4611	0.6379	0.8343
	5%	1.05	-0.5328	0.7887	0.9406
2000 ms	1%	0.975	0.4619	1.3543	2.0348
	1%	1.025	-0.5138	1.6914	2.6375
	5%	0.95	0.4579	0.6271	0.8166
	5%	1.05	-0.5304	0.7743	0.9246
5000 ms	1%	0.975	0.4664	1.3903	2.1522
	1%	1.025	-0.5112	1.6745	2.7632
	5%	0.95	0.4604	0.6583	0.8671
	5%	1.05	-0.5309	0.7421	0.9728

GFMI Islanded Voltage Response

- Inverter Settings
  - 1% and 5% used for testing
  - ITC of 1000, 2000, and 5000 ms tested
- Load Settings
  - Delta configuration inductive load bank
  - Block load from 0 kW to 50kVar (inductive)
- Results
  - Both droops initially respond to block load in approximately 230 ms
  - 5% droop increases to around 550 ms and 1.6 s with increasing ITC
  - 1% droop took upwards of 3.3 s to stabilize at higher ITCs
    - Voltage drop to nearly 0.80 p.u. of V_{nom} at onset of load

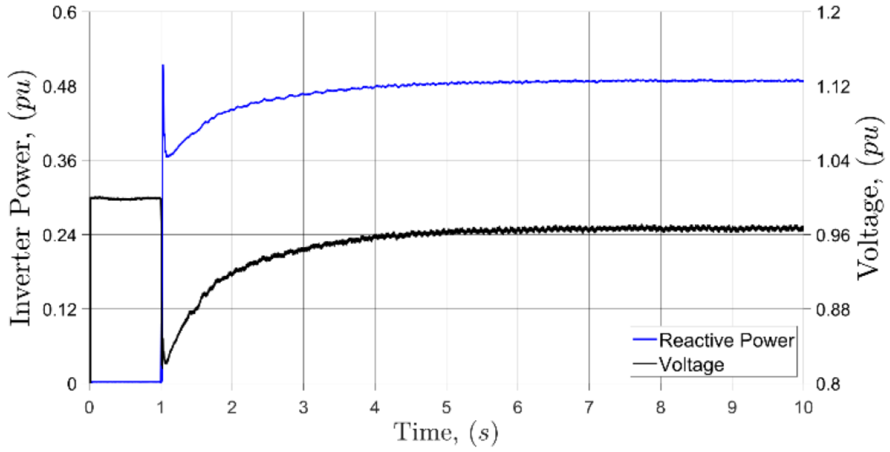


Fig. 5: GFMI, Islanded Voltage Response, 1% droop, 5000 ms Inertia Time Constant, 50kVAr Load

Conclusion and Why this is all Important

- Both GFMIs and GFLIs can be fast responding
  - Going to be limited by control schemes
- GFMIs can pick up the majority of load very quickly
- GFLIs are easily adjustable for standards compliance
- Dependent on control, over adjustment of parameters can lead to instability if not careful

- Understanding how IBRs respond to fluctuations in grid voltage and frequency
- Having flexibility in response time is crucial to better match non-IBRs for grid stability
- Knowing how quickly GFMIs (and GFLIs) can pickup and share load is vital for IBR based microgrids
- Having an understanding where IBRs can go unstable is crucial

Thank You