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## Performance Evaluation of Multi-Vendor Grid-Forming Inverters for Grid-Connected Operation Through Hardware Experimentation

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Jing Wang, Subhankar Ganguly, and Benjamin Kroposki Power Systems Engineering Center, National Renewable Energy Laboratory, Golden, CO 80401, USA

## Abstract

This paper presents the functional performance evaluation tests of multiple (three) commercial grid-forming (GFM) inverters when they operate in parallel with the grid through hardware experiments. The goal of these tests is to explore and benchmark the GFM inverters' functionalities and dynamic response when they are operated in parallel with power grids. Both steady-state (changing the inverter's frequency and voltage droop) and transient (adding step changes to the grid's frequency/voltage) tests are performed for each GFM inverter with the same testing circuit and testing protocol. The key findings are summarized as follows:

(1) The GFM inverters can be dispatched through frequency and voltage droop intercepts to output the target power; (2) the GFM inverters automatically respond to system frequency and voltage events to output the needed power; and (3) all the GFM inverters show stability issues when absorbing reactive power from the grid.

## Motivation

- Existing real-world applications of GFM inverters are typically sized between dozens and a few hundred megawatts.
- The performance of smaller GFM inverters (from dozens to a few hundred kVA) operating in parallel with power grids is less understood.
- There is an opportunity to better understand these GFM inverters through hardware testing under controlled laboratory conditions



#### Specifications of the three commercial GFM inverters

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% at 500	0.83%
Voltage droop settings	5%	10 V gives 7.22 kVar at 2,160	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	Modbus TCP	Modbus TCP

## **Summary of Testing Cases**

## Experimental Results

0.1

0.06

0.25

0.11 0.23 0.48 0.73

0.5

0.75

Target Active Power (p.u.) 0.05

GFM1 P

Test Type	Scenarios	Test Approach					
Steady state	Sourcing power	<ol> <li>With the grid simulator set to nominal voltage and the frequency and inverter voltage droop curve intercept set to achieve 0 or minimal reactive power flow, the inverter frequency droop curve intercept is adjusted to force the inverter to source 5%, 10%, 25%, 50%, 75%, and 100% rated kW.</li> <li>With the inverter frequency droop curve intercept set achieve 0 or minimal real power flow, the voltage droop curve intercept is adjusted to force the inverter to source and sink 5%, 10%, 25%, 50%, 75%, and 100% rated kVAR.</li> </ol>					
	Sinking power	With the grid simulator set to nominal voltage and the frequency and the inverter voltage droop curve intercept set to achieve 0 or minimal reactive power flow, the inverter frequency droop curve intercept is adjusted to force the inverter to sink 25%, 50%, 75%, and 100% rated kW.					
Transient	Frequency step	With the inverter voltage and frequency droop curve intercepts set to nominal values and the grid simulator voltage set to nominal value, the grid simulator frequency is stepped to force the inverter to source and sink 50% and 100% rated kW.					
	Voltage step	With the inverter voltage and frequency droop curve intercepts set to nominal values and the grid simulator frequency set to nominal value, the grid simulator voltage is stepped to source and sink rated kVAR.					
Scenario Inv Scenario intercep the grid	io #1: both are 60 Hz, Gr #2: inverter shifts up t, active power flows side.	no power flow $f_0$					
Scenar droop i grid sic	io #3: inverter shifts c intercept, active power le to the inverter.	lown the frequency $f(p,u,.)$ ar flows from the $f_0$ $p_1 \le 0$ $p_0$					
Dispato	ch rules of GFI grid fr	V inverters for grid-connected operation: equency/voltage changes f (p. u.) fr: Sourcing					



		Q	-0.0	06	-0.	.03	-0.09	-0.21		-0.3	4	-0.42	
		THD_i (%)	65.7	3	33	.54	14.84	7.26		4.9		4.17	
	GFM2	Р	0.02		0.0	08	0.23	0.48		0.73		0.98	
		Q	-0.0	6	-0.	.07	-0.1	-0.15		-0.2	1	-0.27	
		THD_i (%)	51.0	6	39	.34	10.12	5.33		4.01		3.92	
	GFM3	Ρ	0.04		0.1	1	0.23	0.48		0.71		0.94	
		Q	-0.0	1	-0.	.03	-0.06	-0.06		-0.1	4	-0.21	
		THD_i (%)	47.6	5	22	.4	8.11	4.09		2.55		2.37	
e	GFM inve	erters so	urcing	react	tive	e pow	er by sh	ifting u	ıp t	he v	oltag	e droop	
ſ	Target Acti	ve Power (p.	u.) 0.05		0.1		0.25	0.5		0.75		1	
i	GFM1	Q	0.06		0.1	1	0.25	0.49		0.63		0.95	
		Р	-0.02		-0.0	02	-0.01	0.007		0.02		0.05	
		THD_i (%)	51.4	2	33.26		14.29	7.96		6.52		5.57	
	GFM2	Q	0.01		0.04		0.2	0.45		0.69		Inverter	
		Ρ	-0.02	-0.02		03	-0.02	-0.02 -0.01		-0.00	16	tripped	
		THD_i (%)	51.0	6	39.34		10.12	5.33		4.01			
GFM3 Q		Q	-0.00	12	0.06		0.21	0.48	0.48		0.95		
		P	-0.00	-0.009		009	0.006	0.03		0.06		80.0	
THD_i (%)		91.7	91.75		.57	12.33	7.72		6.89		6.49		
,		rtore cink	ina ao	tivo r		vor by	chifting	a down	th		auon	ov droo	
4	in nivei	ters sinn	ing ac	uver		ver by	Simung	y uowii	un	- 110	quen	cy uroo	
h													
ļ	Target Acti	ve Power (p.	.u.) -0.05	;	-0.1	1	-0.25	-0.5		-0.75		-1	
	Target Acti GFM1	ve Power (p. P	. <b>u.) -0.05</b> -0.07		-0.1	1 12	-0.25 -0.26	-0.5 -0.51		-0.75		-1 -1	
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	Target Acti GFM1 GFM2	Pereception Perece	u.) -0.05 -0.07 -0.02 47.3 Inve unst	2 ter able	-0. -0. 0.0 27. -0. -0. 24.	1 12 102 13 12 05 .18	-0.25 -0.26 0.05 13.35 -0.28 -0.01 12.3	-0.5 -0.51 0.14 6.61 -0.54 0.03 8.01		-0.79 -0.77 0.23 4.42 -0.79 0.08 5.52		-1 -1 0.32 3.44 Inverter tripped	
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	Target Acti GFM1 GFM2 GFM3 GFM3 Target Ac (p GFM1 GFM1 GFM2	ve Power (p) P Q THD_i (%) P Q THD_i (%) P Q THD_i (%) P Q THD_i (%) P Q THD_i (%)	u.)         -0.05           -0.07         -0.02           47.3         Inveie           Inveie         unst           -0.07         0.00           27.3         SOURCE           0.22         -0.14           5.06         0.24           -0.09         11.29	22 ter able 6 2 0.47 -0.25 5.05 0.5 -0.11 1.027	-0. 0.0 27. -0. 24. -0. 17. ctiv 5	1 12 12 13 12 05 18 12 2 36 <b>/ e pov</b> <b>0.74</b> -0.21 3.87 <b>0.74</b> -0.21 3.87 <b>0.74</b> -0.21 3.13 <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.75</b> <b>1.76</b> <b>1.76</b> <b>1.76</b> <b>1.76</b> <b>1.76</b> <b>1.76</b> <b>1.77</b> <b>1.76</b> <b>1.76</b> <b>1.76</b> <b>1.76</b> <b>1.76</b> <b>1.76</b> <b>1.76</b> <b>1.77</b> <b>1.76</b> <b>1.76</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b> <b>1.77</b>	-0.25 -0.26 0.05 13.35 -0.28 -0.01 12.3 -0.26 0.06 6.87 <b>ver by c</b> 1 Inverter unstable	-0.5 -0.51 0.14 6.61 -0.54 0.03 8.01 -0.5 0.14 4.51 -0.25 -0.25 -0.002 5.27 -0.25 -0.002 5.27 -0.22 0.02 14.57	9 9 -0.5 0.0 5.2 -0.5 0.0 11.1	-0.75 -0.77 0.23 4.42 -0.75 0.08 5.52 -0.75 0.21 3.26 0.21 3.26 0.5 5 9 7 7 33 7 7	<b>freque</b> -0.75 0.18 3.4 -0.79 0.12 14.7	-1 -1 0.32 3.44 Inverter tripped -0.96 0.28 2.81 <b>ercy</b> -1 0.26 2.54 Inverter ureter -1 0.26 2.54	
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#### GFM inverters sourcing reactive power by reducing grid voltage

Target active power (p.u.)		0.25	0.5	0.75	1.0	
GFM1 Q		0.21	0.42	0.64	0.87	
	P	800.0	0.014	0.033	0.059	
	THD_i (%)	11.93	6.06	4.07	3.15	
GFM2	Q	0.19	0.42	0.6	Inverter unstable	
	P	-0.009	-0.007	0.007		
	THD_i (%)	18.97	9.71	6.25		
GFM3	Q	0.24	0.47	0.68	0.9	
	P	0.02	0.04	0.06	0.08	
	THD_i (%)	14.04	7.93	6.76	6.11	

### Conclusions

This paper studied the dispatchability and interoperability of GFM inverters during grid-connected mode with the intention of informing the GFM inverter industry that:

- GFM inverters can be dispatched like GFL inverters through voltage and frequency droop intercept (v\* and f\*).
- GFM inverters show stability issues when dispatched to absorb reactive power from the grid. Also, when active power is dispatched, a large amount of reactive power is generated.
- Droop settings are critical to achieve the stable dispatch of GFM inverters during grid-connected operation.

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