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

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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:

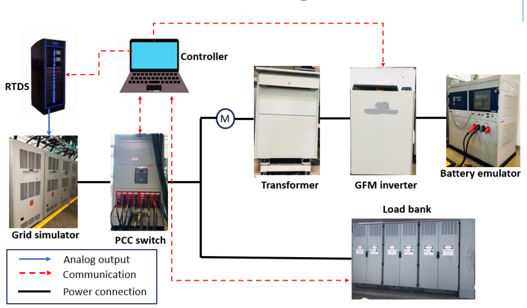
*(1) The GFM inverters can be **dispatched through frequency and voltage droop intercepts** to output the target power; (2) the GFM inverters **automatically respond to system frequency and voltage events to output the needed power**; and (3) all the GFM inverters show stability issues when **absorbing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

Generic Testing Circuit



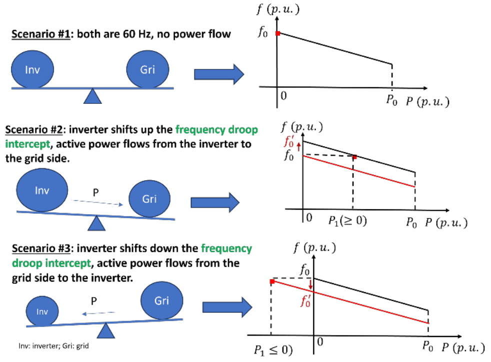
Specifications of the three commercial GFM inverters

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

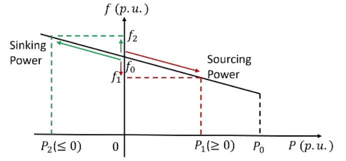
Summary of Testing Cases

Test Type	Scenarios	Test Approach
Steady state	Sourcing power	1. 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. 2. With the inverter frequency droop curve intercept set to 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.
	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.

Dispatch rules of GFM inverters for grid-connected operation: GFM inverter frequency/voltage droop intercept changes



Dispatch rules of GFM inverters for grid-connected operation: grid frequency/voltage changes



Experimental Results

GFM inverters sourcing active power by shifting up the frequency droop

Target Active Power (p.u.)		0.05	0.1	0.25	0.5	0.75	1
GFM1	P	0.06	0.11	0.23	0.48	0.73	0.9
	Q	-0.006	-0.03	-0.09	-0.21	-0.34	-0.42
	THD_i (%)	65.73	33.54	14.84	7.26	4.9	4.17
GFM2	P	0.02	0.08	0.23	0.48	0.73	0.98
	Q	-0.06	-0.07	-0.1	-0.15	-0.21	-0.27
	THD_i (%)	51.06	39.34	10.12	5.33	4.01	3.92
GFM3	P	0.04	0.1	0.23	0.48	0.71	0.94
	Q	-0.01	-0.03	-0.06	-0.06	-0.14	-0.21
	THD_i (%)	47.65	22.4	8.11	4.09	2.55	2.37

GFM inverters sourcing reactive power by shifting up the voltage droop

Target Active Power (p.u.)		0.05	0.1	0.25	0.5	0.75	1
GFM1	Q	0.06	0.11	0.25	0.49	0.63	0.95
	P	-0.02	-0.02	-0.01	0.007	0.02	0.05
	THD_i (%)	51.42	33.26	14.29	7.96	6.52	5.57
GFM2	Q	0.01	0.04	0.2	0.45	0.69	Inverter tripped
	P	-0.02	-0.03	-0.02	-0.01	-0.006	
	THD_i (%)	51.06	39.34	10.12	5.33	4.01	
GFM3	Q	-0.002	0.06	0.21	0.48	0.730.95	
	P	-0.009	-0.009	0.006	0.03	0.06	0.08
	THD_i (%)	91.75	35.57	12.33	7.72	6.89	6.49

GFM inverters sinking active power by shifting down the frequency droop

Target Active Power (p.u.)		-0.05	-0.1	-0.25	-0.5	-0.75	-1
GFM1	P	-0.07	-0.12	-0.26	-0.51	-0.77	-1
	Q	-0.02	0.002	0.05	0.14	0.23	0.32
	THD_i (%)	47.32	27.13	13.35	6.61	4.42	3.44
GFM2	P	Inverter unstable	-0.12	-0.28	-0.54	-0.79	Inverter tripped
	Q		-0.05	-0.01	0.03	0.08	
	THD_i (%)		24.18	12.3	8.01	5.52	
GFM3	P	-0.07	-0.12	-0.26	-0.5	-0.75	-0.96
	Q	0.006	0.02	0.06	0.14	0.21	0.28
	THD_i (%)	27.32	17.36	6.87	4.51	3.26	2.81

GFM inverters sourcing active power by changing grid frequency

Target Active Power (p.u.)		0.25	0.5	0.75	1	-0.25	-0.5	-0.75	-1
GFM1	P	0.22	0.47	0.74	Inverter unstable	-0.25	-0.5	-0.75	-1
	Q	-0.14	-0.25	-0.21		-0.002	0.09	0.18	0.26
	THD_i (%)	5.06	5.05	3.87		5.27	5.27	3.4	2.54
GFM2	P	0.24	0.5	0.74	Inverter unstable	-0.28	-0.53	-0.79	Inverter unstable
	Q	-0.09	-0.11	-0.16		0.02	0.07	0.12	
	THD_i (%)	11.29	1.027	13.21		14.57	11.74	14.7	
GFM3	P	0.24	0.47	0.7	Inverter unstable	-0.24	-0.49	-0.74	Inverter unstable
	Q	-0.1	-0.17	-0.25		0.05	0.13	0.2	
	THD_i (%)	9.87	3.77	2.71		11.87	5.0	6.64	

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	0.008	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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