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

Preprint

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

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***Abstract*—Standardized experimental testing protocols for grid forming (GFM) inverters to ensure expected operation under both normal and contingency conditions do not exist. Such protocols increase the confidence of system owner/operators that an inverter deployed in a proposed system will engage in typical behaviors to ensure interoperability with other units and ancillary equipment (e.g. protection equipment). This paper presents systematic and comprehensive test protocols to evaluate the performance of GFM inverters under the following operational configurations: islanded operation, heterogeneous islanded operation (parallel with a synchronous generator), grid-connected operation, and transition operation. A commercial GFM inverter is used to verify the test protocols and to understand the inverter's performance and functionalities. In particular, required configuration and tuning of the inverter will be explained in the full paper to enrich the testing protocol.**

***Index Terms*—Black start, droop control, grid-forming inverters, grid-following inverters, transient stability.**

I. INTRODUCTION

In the recent years, grid-forming (GFM) inverters have shown significant advantages for improving the strength and stability of electric grids, compared to systems composed primarily of grid-following (GFL) inverters [1]. To understand the capabilities of GFM inverters, performance evaluation should be conducted to test the GFM inverter's performance under various scenarios. Overall, existing work related to performance evaluation of GFM inverter are mainly carried out through electromagnetic transient (EMT) simulation, such as testing islanding operation and black start capability of a commercial GFM inverter [2], evaluating improved controls of GFM inverter for fault ride-through in a microgrid [3], and validating the innovative GFM inverter control for smooth microgrid transition operation [4]. There are also a few research activities performing experimental performance evaluation of GFM inverter, including testing GFM inverter performance under balanced and fault conditions [5], black start [6], and system contingency support [7].

Typically, previous research has focused on a single operational configuration due to their specific system applications or function requirements. To the authors' knowledge, there are no works which adopt a wholistic, systematic approach to evaluating GFM inverter performance for a wide range of operating modes. However, evaluating GFM inverter performance comprehensively, especially through experimental testing, is very important because it provides an extensive insight of GFM inverter capabilities, allowing for informed decision making for many utilities and reducing technological risk for system insertion. Therefore, this paper aims to develop testing protocols for experimental characterization testing of a GFM inverter, which addresses the gap of comprehensive testing in existing works. Since evaluating the GFM inverter under complex power grids is very challenging, the proposed testing protocol is developed through a small system (microgrid). The main contributions of the paper are to: 1) develop testing protocols (e.g., characterization approaches and scenarios) for engineers who need to perform comprehensive performance evaluation of GFM inverters; 2) provide insights on the configuration and tuning for Blackbox testing of GFM inverter; and 3) produce recommendations of performance metrics for GFM inverters that can be used for device-to-device comparisons.

II. DESCRIPTION OF THE CHARACTERIZATION TEST

A. Testing Objective

The objective of this experimental characterization testing is to comprehensively evaluate GFM inverter performance

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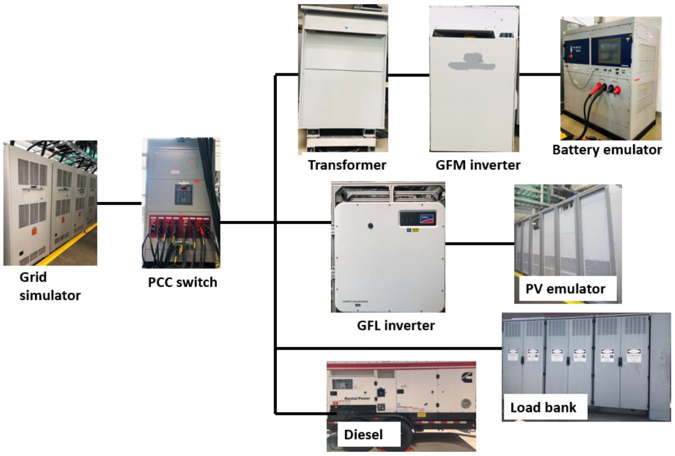


Fig. 1: Laboratory experiment setup.

under a wide range of operational conditions. To achieve this, we will evaluate inverter autonomous response under a variety of scenarios when operating stand-alone, in parallel with a synchronous machine, or connected to a larger grid. To be more specific, the main objectives of the testing are: 1) analyze power quality of the inverter under both steady-state and transient conditions; 2) evaluate the active and reactive power, overload, black start, and synchronization capabilities of the inverter; and 3) characterize inverter dynamic response, including secondary control, load step, loss of generation etc.

B. *Testing Scenarios and Performance Metrics*

Table. I summarizes all the testing scenarios. For steady-state testing, performance metrics include root mean square (RMS) voltage and current, active and reactive power, voltage and current total harmonic distortion (THD), and frequency. For the transient testing, performance metrics include peak deviations, settling time and response time, transient distortion, in addition to all parameters from steady-state testing.

III. DESCRIPTION OF GFM INVERTER AND TESTING CIRCUIT

A. *Description of the GFM Inverter*

The GFM inverter under test is an off-the-shelf inverter with a capacity of 250 kVA. The inverter can operate in three modes: islanded control (VF control), grid-tied control (PQ control), and grid-supporting (VF/PQ control).

B. *Testing Circuit*

Fig. 1 shows the testing circuit, which includes the GFM inverter with a battery emulator on the DC side and a delta:wye transformer at the AC output as well as other supporting equipment, including a GFL inverter, a diesel generator, load banks, a nonlinear load, a grid simulator (540 kVA), an induction motor, and a microgrid switch. This is the full testing circuit, and only a subset of the devices will be connected for any given specific testing scenario. Note that the measurement point is at the Y-side of the transformer.

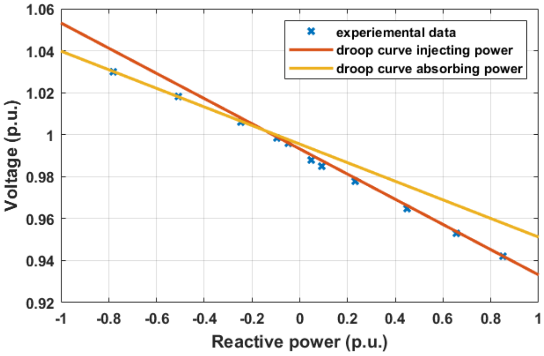


Fig. 2: Voltage droop characterization for the inverter.

IV. TESTING CONFIGURATION

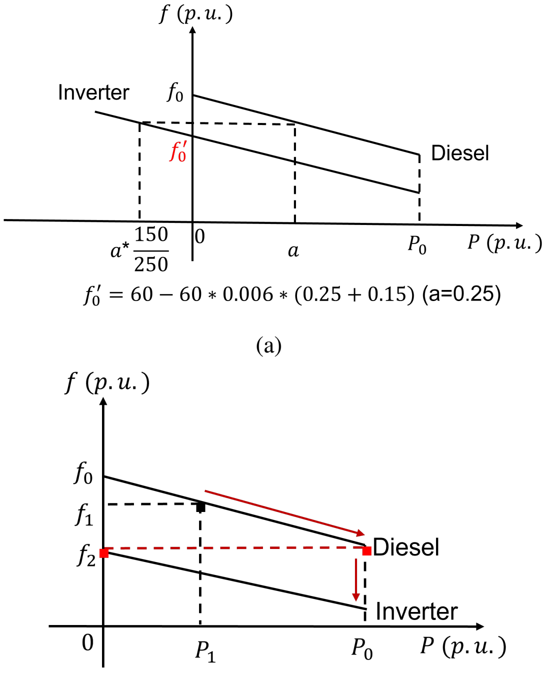
The GFM inverter can operate in three modes: islanded control mode, grid-tied control mode, and grid-supporting function. In the grid-tied (also GFL) mode, the inverter can be controlled through active and reactive power command. In the islanded control mode (also GFM mode), the inverter controls its voltage and frequency based on droop (frequency-active current and voltage-reactive current). The default droop coefficients are: 0.25% for frequency and 5% for voltage. The inverter can also work in grid-support function to support grid voltage and frequency by operating in parallel with the grid as a GFM inverter or as a GFL inverter. In our test, the inverter is configured always as GFM control even it is grid-connected. Due to the delta:wye transformer, the voltage droop of the GFM inverters is no longer accurate because of the reactive power consumed by the transformer; therefore, we characterize the droop of the GFM inverters by treating the inverter and the transformer as a whole. Based on the standalone test with pure resistance, inductive and capacitance loads of different set-points (5%, 10%, 25%, 50%, 75%, and 100%), we can obtain the fitting droop curve as shown in Fig. 2. Fig. 2 shows the droop curve using the experimental data, and two matching curves are derived for injecting and absorbing reactive power, respectively. The droop curve is $v^* = v_0 - n * Q$, with $v_0 = 0.9932$, $n = 6\%$ for injecting reactive power and $v_0 = 0.9955$, $n = 4.43\%$ for absorbing reactive power on a per-unit basis. The frequency droop is defined as $f^* = f_0 - m * P$ with f_0 the frequency droop intercept and equal to 1, and m is the frequency droop scope, equal to 0.25%.

A. *Stand-alone Islanded Operation*

For stand-alone islanded operation, the GFM inverter keeps the same droop settings (droop coefficients and droop intercepts) for the steady-state and transient testing listed in Table 1 except for the secondary control testing. For secondary control, we aim to regulate the system voltage and frequency to their nominal values. This is achieved by shifting the droop intercepts up by the corresponding deviations. The new frequency droop intercept can be derived as: $f_0 = 60 + m * 60 * P$. For voltage secondary control, the new voltage droop intercept can be derived as: $v_0 = 480 + n * 60 * Q + (1 - 0.9932) * 480$ for inductive load ($Q \geq 0$), and $v_0 = 480 + n * 60 * Q + (1 - 0.9955) * 480$ for capacitor load ($Q \leq 0$).

B. *Heterogeneous Islanded Operation*

We use the default frequency droop coefficient (0.25%) for all the standalone testing. However, this droop slope is too small which is considered to be a stiff system and hard to parallel with another GFM source (e.g., a diesel generator). Therefore, we change the frequency droop to a larger value (0.6%) which shows good stability when the inverter parallels to the diesel. Note that the diesel is 150 kVA. For most of the testing, we keep the droop the same for both the inverter and the diesel generator except the uneuqal power sharing testing scenario. For all the testing under heterogeneous islanded operation, the sinking power and the unequal power scenarios need more attention. Fig. 3 shows the configuration of these two testing scenarios. Fig. 3a shows the sinking power with 25% loading as an example. Since the diesel is the smaller one, the 25% refers to the 0.25 p.u. of the diesel, then the power sank by the inverter will be $a * 150/250$ in p.u.. To allow the inverter sinking 25% power from diesel, the inverter needs to shift the droop intercept down by $0.006*60*(0.25+0.15)$ Hz. Fig. 3b shows the inverter and diesel start from equal power sharing (f_1 and P_1) with the load equally to the size of the smaller one between diesel and the inverter (150 kW), then the inverter contributes 0% power by shifting the droop intercept down and the diesel generator contributes 100% power to supply the load with the new frequency operating point of f_2. To achieve this power dispatch, the inverter needs to shift the droop intercept downwards by $0.006 * 60 * (1 - 0)$ Hz.



(a)

(b)

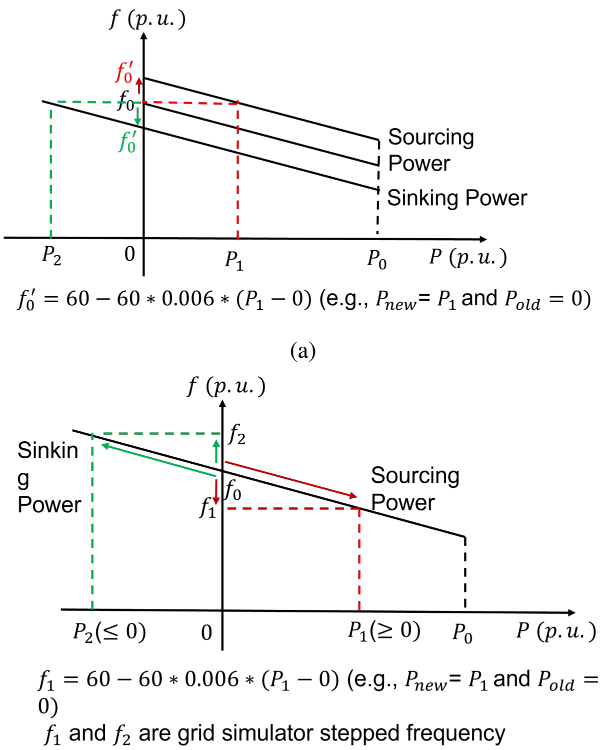
Fig. 3: Heterogeneous Islanded Operation: a) sinking power with 25% loading, b) unequal power sharing with 0% power from the inverter.

C. *Grid-connected Operation*

Since the grid simulator is a stiff voltage source with output voltage magnitude and frequency equal to nominal values, the GFM inverter needs to follow the grid simulator. If there is no dispatch (changing the droop intercepts), the GFM inverter theoretically just outputs zero active and reactive power based on the droop curves. To achieve the target power generation for steady state inverter sourcing (generating) and sinking (absorbing) power as outlined in Table 1, the basic rule of dispatching the GFM inverter is to shift the droop intercept as follows: 1) if the goal is to generate active power, the frequency droop intercept needs to shift up by $m * 60 * (P_{new} - P_{old})$ with P_{new} the target active power output, and P_{old} the previous active power output; 2) if the goal is to absorb active power, the frequency droop intercept needs to shift down by $m * 60 * (P_{old} - P_{new})$ with P_{new} the target active power output, and P_{old} the previous active power output. Similar rules apply to the reactive power generation. For grid simulator frequency and voltage steps testing to force inverter sinking/sourcing desired amount of power, the configuration rules are outlined as follows: 1) if the goal is to force the inverter generate desired amount of power (P_{new}), then the grid simulator needs to shift the frequency down by $m*60*(P_{new} - P_{old})$ with P_{new} the target active power output, and P_{old} the previous active power output of the inverter; 2) if the goal is force the inverter absorb desired amount of power, the frequency of the grid simulator needs to shift down by $m * 60 * (P_{old} - P_{new})$ with P_{new} the target active power output, and P_{old} the previous active power output. Similar rules apply to the inverter reactive power dispatch by stepping the voltage reference of the grid simulator. Fig. 4 generally explains the way how to achieve the dispatch of the GFM inverter in grid-connected operation mode.

D. *Transition Operation*

The transition operation starts from islanded operation with the GFM inverter supplying 50% PF=1, 0.8 lagging and leading load (three scenarios), then the system synchronizes to the grid simulator, operates in grid-connected mode, then intentionally open the PCC circuit breaker to islanding the system. To achieve smooth transition operation, the rule of thumb is to minimize the PCC power flow and keep the GFM inverter operate at the same operating point (f, P, V and Q) before and after the transition operation [8]. During our test, there is an issue for the inverter synchronizing with the grid simulator with a load connected. Therefore, the synchronization test is only performed with the inverter itself synchronizes to the grid simulator and the load. With this setup, the inverter always operates with near-zero power output after synchronization operation, and then we need to dispatch the inverter to supply all the load to have the PCC power flow minimized before islanding operation and have



(a)

(b)

Fig. 4: Grid-connected operation: a) sinking/sourcing power steady state operation, b) grid simulator voltage and frequency steps.

the inverter maintain the same operation point before and after islanding operation. For PF=1 load, the frequency droop intercept needs to be shifted up by $\Delta f = m * 0.5 * 60$ Hz; for PF 0.8 lagging load, the frequency droop intercept is shift up by $\Delta f = m * 0.5 * 0.8 * 60$ and the voltage droop intercept is shift up by $\Delta v = n * 0.5 * 0.6 * 480 + (1 - 0.9932) * 480$ V; for PF 0.5 leading load, the frequency droop intercept is shift up by $\Delta f = m * 0.5 * 0.8 * 60$ Hz and the voltage droop intercept is shift down by $\Delta v = n * 0.5 * 0.6 * 480 + (0.9955 - 1) * 480$ V.

V. EXPERIMENTAL RESULTS

The experimental tests are performed based on the testing scenarios defined in Table I. Due to the limited space, selective results of steady state testing are briefly summarized and only representative testings results for transient testing are presented in figures. The results are presented based on four testing configuration.

A. Stand-alone islanded operation

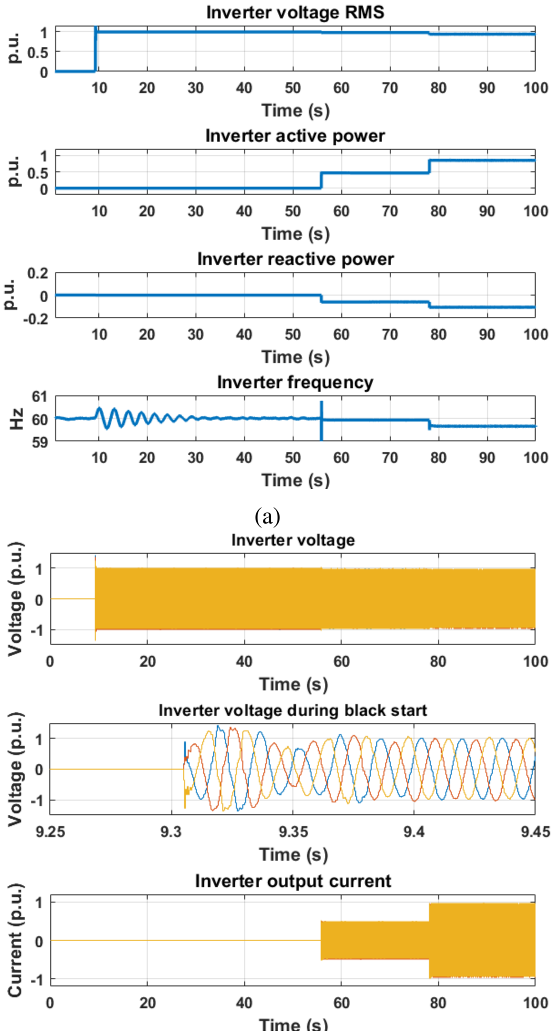
Balanced load: 1) the inverter can operate full spectrum of its active and reactive power capability; 2) The inverter's current and voltage THD are mostly below 5% except PF 0.8 leading 5% and 10% and 100% capacitive; 3) the frequency droop matches with the default settings but the voltage droop is off (the intercept is not at "1" p.u. and the slope is different from the default settings; 4) inverter voltage drops below 0.95 p.u. at 100% PF=1, 0.8 lagging and leading. Unbalanced load: inverter is able to handle all the tested unbalanced loading, the THD of voltage and current is always below 5%, the voltage imbalance is below 0.25%. Sinking power: the inverter is able to absorb the excessive active and reactive power from the GFL inverter, and the THD of current and voltage are worst when the power contribution from the GFM inverter is zero. Load step: the inverter is able to handle all the load steps defined in the Table I. Overloading: the inverter is able to handle all the listed overloading testing except PF 0.8 lagging and leading from 1.6 p.u., and the duration of overloading is between 5 and 9 seconds.

Since black start is an important function for GFM inverter, the testing results of black start are presented. The inverter connects with a 500 kVA delta:wye transformer and a load bank with 250 kW (equal to the KVA rating of the inverter). The test starts with the inverter energizing the transformer, then connects to 50% load, and finally 100% load. The whole process took 100 seconds. The key measurements are shown in Fig. 5. The results show that the inverter does not have a soft black start. That's why the starting up voltage shows oscillations. And the voltage settles down after 0.1 second. For 50% and 100% load connection, the inverter reaches steady-state within less than 2 cycles. The black start was successful.

The results of secondary control are presented in Fig. 6. For frequency regulation testing, 50% PF=1 load is applied. As seen from the result, the frequency is regulated to nominal value. The response time is around 0.01 seconds, and the settling time is less than 0.3 seconds. For voltage regulation testing, 50% pure inductive load is applied. As seen from the result, the inverter is able to regulate its voltage into nominal value. The response time is immediately, and the settling time is around 0.23 seconds.

B. Heterogeneous islanded operation

In this scenario, the steady state testing results are summarized as follows: 1) Balanced load: the inverter and diesel are configured to have the same droop: $f = 1 - 0.6\% * P$ and $v = 1 - 6\% * Q$. The main observations are summarized as follows: 1) the inverter can equally share the active power with diesel in p.u. basis, and the reactive power sharing has noticeable errors (the inverter shares less reactive power); 2) the frequency exhibits high oscillations with lower load; 3) voltage THD is below 5% and current THD is above 5% with 5% and 10% loading and the worst THD is under the lowest load; 4) the inverter responds faster than the diesel when the load is increased. 2) Sinking power: for active power, the inverter frequency droop is shifted down by $\Delta f = 0.006 * (P + 0.6P) * 60$ Hz to absorb power from the diesel. 1) the inverter can absorb the desired amount of active power from the diesel; 2) voltage THD is below 3%, the current THD is below 5%. 3) the inverter frequency is very oscillating. For reactive power, the inverter voltage droop is shifted down by $\Delta v = 0.068 * (Q + 0.2Q) * 480$ Hz to absorb reactive power from the diesel. 1) the reactive power absorbed



(a)

(b)

Fig. 5: Standalone islanded operation - black start: a) key measurements in RMS, b) inverter voltage and current waveforms.

by the inverter is lower than the target; 2) voltage THD is below 3%, the current THD is below 5%. 3) the inverter frequency is very oscillating.

We select the transient testing of unequal power sharing for 90% power scenario. The test starts with equal power sharing of the load equal to the size of the smaller of the inverter and the diesel, and then we move the frequency droop intercept of the inverter to let inverter supply 90% of the load. Based on the calculation, the equal power sharing is $150/(150+250) = 37.5\%$. Then, we move to 90% power sharing for the inverter, this will be 0.9*150/250=0.54 p.u.. For diesel, the shared power will be: 0.1*150/150=0.1 p.u.. To achieve this, the frequency droop intercept of the inverter needs to be shifted up by $\Delta f = 0.6\% * (0.54 - 0.1) * 60 = 0.1584$ Hz. Only one step is taken to complete the test. The voltage THD is between 1.12% and 1.26%, and the current THD is between 2.4% and 3.57%. The results shown in Fig. 7 indicate that the inverter supplies 90% load.

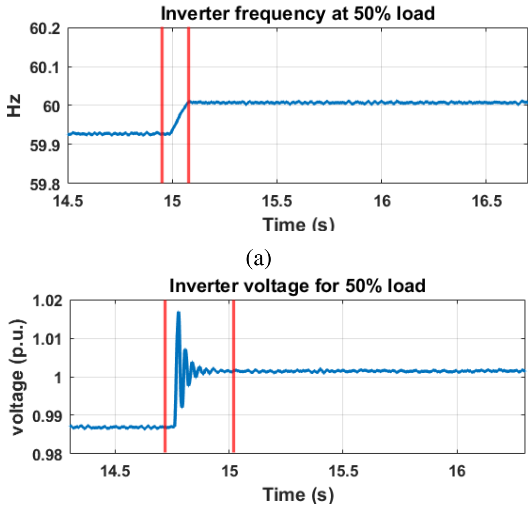


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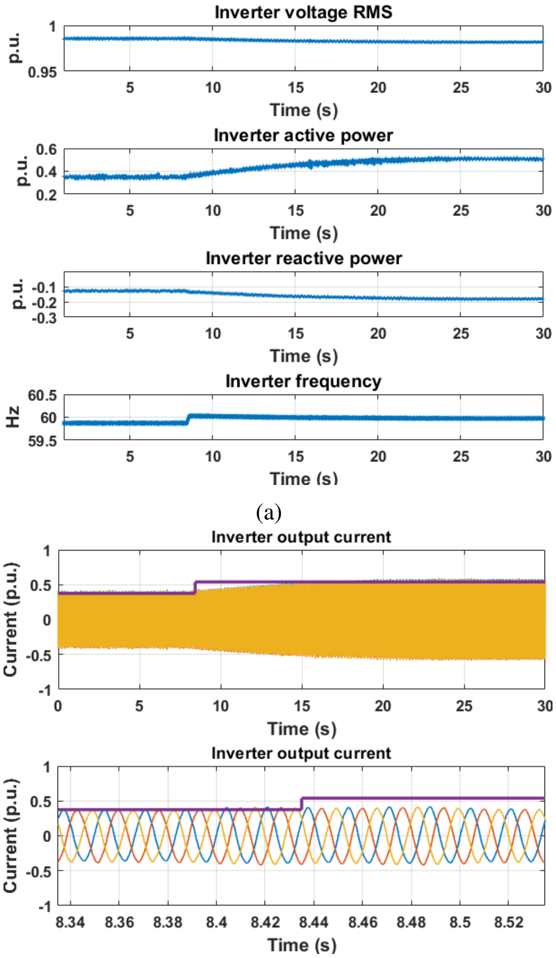
Fig. 6: Standalone islanded operaiton - secondary control: a) frequency secondary control, b) voltage secondary control.



(a)

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Fig. 7: Heterogeneous islanded operation - unequal power sharing: a) key RMS measurements, b) inverter current waveforms.

C. Grid-connected operation

In this scenario, the steady state testing results are summarized as follows: 1) Sourcing active power: The inverter frequency droop intercept is shifted up by $\Delta f = 0.006 * P * 60$. The observations are summarized as follows: a) there is small amount of current (very noisy) when the frequency droop intercept is not shifted; b) inverter outputs the target active power except the 100% loading condition (the inverter only outputs 90% because the reactive power de-rates the inverter); c) voltage THD is below 0.5%, and current THD is high with low power (e.g., 657% for 5%) and from 75% up to 100%, the THD is below 5%; d) there is no overshoot in the inverter output current when the frequency droop intercept is shifted up; and e) the reactive power output (absorbing power) from the inverter increases when the loading increases, e.g., the reactive power is 0.42 p.u. with 100% loading. 2) Sourcing reactive power: the inverter voltage droop intercept is shifted up by $\Delta v = 0.06 * Q * 480 + (1 - 0.9932) * 480$. The observations are summarized as follows: a) inverter outputs the reactive power slightly lower than the expected value and the system voltage is maintained at nominal; b) voltage THD is below 0.6%, and current THD is high with low power (e.g., 51.4% for 5%) and is all above 5%; c) the inverter output current also exhibits oscillations when the voltage droop intercept is shifted up, and the higher reactive power output, the larger the oscillations, but inverter settles down in less than 1 second; d) the active power (absorbing power) of the inverter is kept very low (less than 0.06 p.u.) for all the testing. 3) Sinking active power: The inverter frequency droop intercept is shifted down by $\Delta f = 0.006 * P * 60$ to absorb power from the grid simulator. The observations are summarized as follows: a) We are able to complete all the testing; b) the inverter absorbs the target active power; c) the output current of the inverter does not exhibit oscillations after the voltage droop intercept is shifted up, and there are no overshoots for all the testing; d) the inverter sinks active power slightly higher than expected; e) the voltage THD is below 0.5%, and the current THD is above 5% from 5% to 50%.

For transient testing, we are able to perform all the test, however, the inverter has bad oscillations when the grid simulator voltage steps up to allow the inverter absorb reactive power. We select one test of the grid simulator's frequency step down and voltage step up to enable the inverter output target active (50%) and reactive (50%) power, respectively. Fig. 8 shows that the inverter actually outputs the desired amount of active and reactive power. But the test with grid simulator stepping up voltage has bad oscillations.

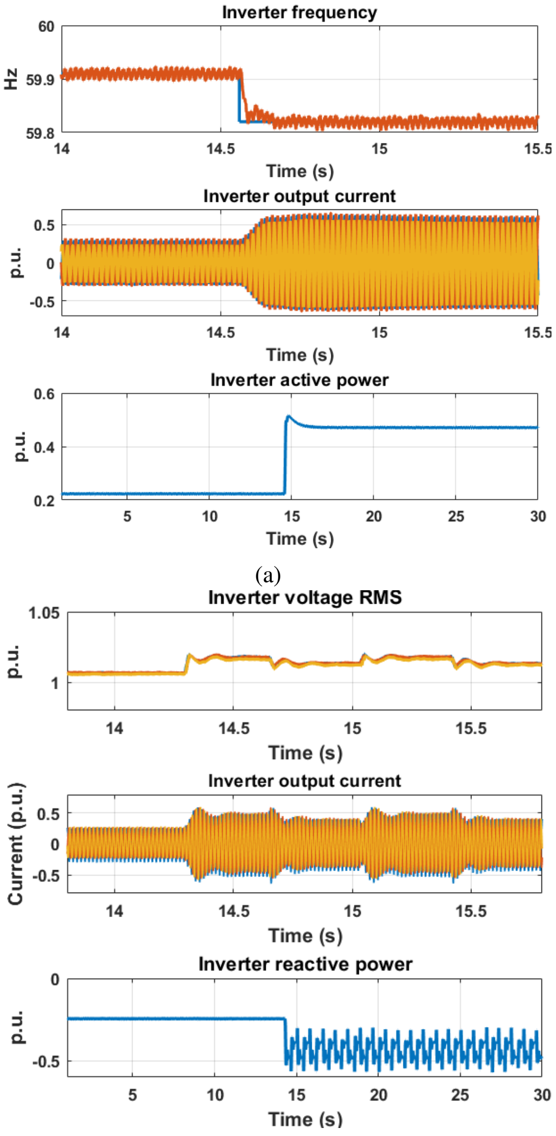

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Fig. 8: Grid-connected operation: a) grid simulator step down frequency; b) grid simulator step up voltage.

D. Transition operation: re-synchronization and islanding operation

For the three scenarios (PF=1, PF 0.8 lagging and leading), we select the PF 0.8 lagging scenario to present the transition operation results. The inverter connects to a grid simulator with a 125 kVA load PF 0.8 lagging (50%) because the inverter has issue connecting to the grid simulator with a load connected. Therefore, we only synchronize the inverter with the grid simulator when there is no load connected to the inverter. Then, the inverter operates in grid-connected mode for some time, we dispatch the inverter to minimize the power flow at PCC ($f^* = 60.144$ Hz and $V^* = 491.904$ V). When PCC power is closed to zero, we disconnect the PCC switch to have the system operate in islanded mode. The inverter operates at the same operating point before and after islanding operation. Fig. 9 shows key measurements of the inverter and PCC during the transition operation including synchronization, dispatch inverter during grid-connected mode and islanding operation. When the inverter synchronizes to the grid simulator, the inverter output current has some oscillations and settles down after 2.5 seconds. When the inverter is dispatched around 15 seconds, there are some oscillations and overshoots in the inverter's output current. The inverter

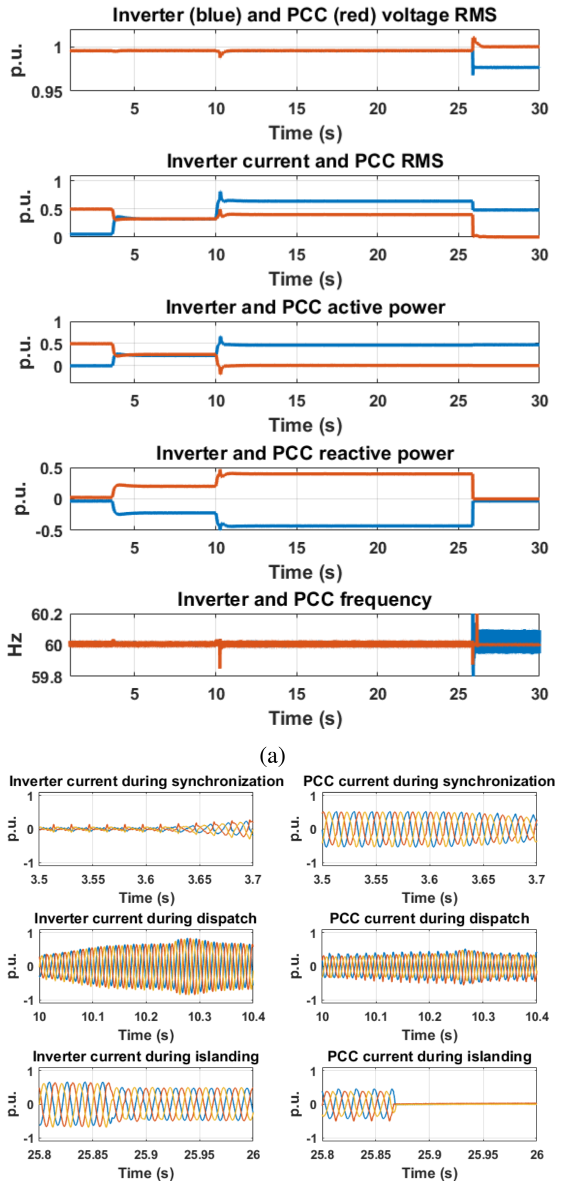

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Fig. 9: Transition operation with PF=1 50% load: a) key RMS measurements of the inverter and PCC, b) current wave-forms of the inverter and PCC.

settles down after 0.5 seconds. When the islanding operation is performed, the inverter shows smooth transition without noticeable transients, and settles down within two cycles. The results indicate a smooth transition operation is achieved with the PF 0.8 lagging 50% loading condition.

CONCLUSION

This paper presents a testing protocol to perform comprehensive laboratory experimental testing for GFM inverters to understand their performance and functionalities. The testing protocol includes stand-alone operation, heterogeneous islanded operation, grid-connected operation, and transition operation. One commercial GFM inverter is used as an example to verify the testing protocol. More importantly, the configuration and tuning of the inverter (Black-box) for the different testing scenarios are presented and we conclude that the inverter can be dispatched through frequency and voltage droop intercepts to achieve the desired power output. Comprehensive laboratory pure hardware experiments are carried out and verified the testing protocol. Due to limited space, only representative results are presented. Our key findings are summarized as follows: 1) The frequency and voltage droop of the inverter need to be characterized; 2) tuning droop slope can easily cause stability issue thus changing the droop intercept is recommended; 3) through the adjusting the inverter droop intercept, we can perform secondary control, and dispatch GFM inverter like we dispatch GFL inverter to output target power; 4) reactive power sharing is a problem that reactive power an re-rate the inverter without proper control; 5) it is important to know the acceptable droop intercept step for stable operators; and 6) stepping up the grid simulator's voltage to let the inverter absorb reactive power causes bad oscillations, and the oscillations get worse with higher reactive power absorbed by the inverter.

Future research work will focus on designing a secondary voltage control to better manage the reactive power sharing.

ACKNOWLEDGMENTS

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TABLE I: Summary of all testing cases for individual inverter

Configuration	Test Type	Scenario	Test Approach
Stand-alone operation	Steady state	Balanced load	Power factor (PF) 1, PF 0.8 lagging and leading, pure inductive and capacitive, representing 5%, 10%, 25%, 50%, 75% and 100% loading of the inverter capacity.
		Unbalanced load	Fixed load at half of the inverter capacity (3-phase), and unbalanced single-phase load (PF 1, 0.8 lagging, 0.8 leading, 10%, 50% and 100% of single-phase capacity.
		Nonlinear load	The nonlinear load (or combination of loads) should be of similar kVA rating as the inverter and tests should be repeated for operation of the nonlinear load(s) at 10%, 50%, and 75% of inverter kVA rating.
		Sinking power	The inverter will be operating in parallel with a GFL inverter which is supplying more power than available load on the islanded power system.
	Transient	Black start	Two tests will be performed. In one test, starting from OFF, the inverter will energize its local area power system with no load and then 50%, and 100% of Inverter rated kVA PF=1 load applied, but there may not be any additional transformers in the local area power system. In the other test, starting from OFF, the inverter must energize a transformer of similar kVA size. This transformer is in addition to any transformer provided with the inverter.
		Load steps	Balanced three-phase linear load steps with power factors of 1, 0.8 lagging, and 0.8 leading. The load steps will be performed between 0 to 50%, 50% to 100% and 0 to 100% of inverter kVA rating.
		Inductive inrush	Two tests will be performed, one with transformer and one starting a motor. This test is different than the black start test above as the local area power system will already be energized and voltage must remain within acceptable limits during the inrush event. For the transformer test, the transformer kVA rating should be XX% of the inverter kVA rating. For the motor test, the motor HP should be XX% of the Inverter kVA rating.
		Overload	The inverter will be subjected to 150% up to 200% overcurrent at power factors of 1 and 0.8 lagging and leading. The overload will be held for XX ms, X seconds, and then indefinitely until the inverter trips.
		Secondary control	The inverter will be tested for its ability to respond to secondary control setpoints, for example the setpoints could represent the 60 Hz real power intercept and 480 V reactive power intercept on P/f and Q/V droop curves, or they could represent the zero-kW frequency intercept and zero kVAR voltage intercept on the same curves.
Heterogeneous is-landed operation	Steady state	Balanced load	Balanced three-phase linear loads with power factors of 1, 0.8 lagging, and 0.8 leading and representing 5%, 10%, 25%, 50%, 75%, and 100% of the combined inverter plus synchronous machine kVA rating. Tests will be run with the inverter and diesel generator having equal voltage and frequency droop intercepts.
		Sinking power	With no load applied, inverter voltage and frequency droop intercepts will be individually adjusted so that the inverter is sinking the smaller of the inverter vs diesel generator kW and kVAR ratings, with 25%, 50%, 75%, and 100% loading.
	Transient	Load steps	Balanced three-phase linear load steps with power factors of 1, 0.8 lagging, and 0.8 leading. The load steps will be performed between 0 and 50%, 50% and 100% and 0 and 100% of the combined inverter plus diesel generator kVA rating.
		Overload	These tests will be performed with balanced three-phase PF=1 load representing 50% of the combined kVA rating of the inverter plus diesel generator. The inverter frequency droop setpoint will set so that the inverter is taking twice the load (on a PU basis) as the diesel generator. The load will then be stepped to a value which would according to a linear droop curve require the inverter to jump to 110% loading. The overload will be held for XX ms, X seconds, and then indefinitely until the inverter trips.
		Loss of generation	Balanced three-phase PF=1 load representing 100% of the inverter kVA rating. The diesel generator will be intentionally tripped offline.
		Secondary control	The same as stand-alone secondary control.
Grid-connected	Steady state	Sourcing power	With grid simulator set to nominal voltage and frequency and inverter voltage droop curve intercept set to achieve 0 or minimal reactive power flow, inverter frequency droop curve intercept will be adjusted to force inverter to source 5%, 10%, 25%, 50%, 75% and 100% rated kW. With inverter frequency droop curve intercept set to achieve 0 or minimal real power flow, voltage droop curve intercept will be adjusted to force inverter to source and sink 5%, 10%, 25%, 50%, 75% and 100% rated kVAR.
		Sinking power	With grid simulator set to nominal voltage and frequency and inverter voltage droop curve intercept set to achieve 0 or minimal reactive power flow, inverter frequency droop curve intercept will be adjusted to force inverter to sink 25%, 50%, 75% and 100% rated kW.
	Transient	Freq and voltage steps	With inverter voltage and frequency droop curve intercepts set to nominal values and grid simulator voltage set to nominal value, grid simulator frequency will be stepped to force inverter to source and sink 50% and 100% rated kW. With grid simulator frequency set to nominal value, grid simulator voltage will be stepped to source and sink rated kVAR.
Transition operation	Transient	Synchronize a small system to the grid, and islanding	During this test, the inverter is initially operating as single source energizing a local area power system. The local area power system can connect to a larger grid, which may be an actual utility grid or may be emulated using a grid simulator. Once system is in steady state, planned islanding is performed.