Droop Control-Based Dispatch of an Islanded Microgrid with Multiple Grid-Forming Sources

Preprint

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Droop Control-Based Dispatch of an Islanded Microgrid With Multiple Grid-Forming Sources

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***Abstract*—Before rotating, fossil fuel-based, synchronous generators (SGs) are phased out, in line with renewable generation goals, grid-forming (GFM) inverters are expected to parallel SGs. Primary droop control allows GFM inverters to share power without communication; however, it is necessary to dispatch GFM inverters and/or SGs with the desired output power for better energy management (e.g., one GFM inverter needs to charge the battery due to a low state of charge). Therefore, this paper develops an analytic approach to dispatching GFM inverters and SGs with the desired output power by shifting the droop intercept up/down while maintaining the same frequency operating point for improved transient stability. This concept is demonstrated through a pure hardware setup with two off-the-shelf inverters and one diesel generator under an islanded microgrid, and we provide insight on the real-world implementation of the proposed concept.**

Keywords—Droop control, grid-forming control, grid-following control, microgrid.

I. INTRODUCTION

In recent years, grid-forming (GFM) inverters have shown significant advantages for improving the strength and stability of electric grids compared to systems primarily comprising grid-following (GFL) inverters [1]. In particular, GFM inverters have been mostly installed in microgrids (MGs) to enhance resilience because they can form the system voltage when the main grid is not available. Many existing and to-be-built MGs have renewable generation plans (e.g., 20% renewable penetration) toward reaching the ultimate goal of 100% renewable generation MGs [2]. On this pathway, synchronous generator (SG)-based generation will still play a role as a GFM generation source, especially in islanded MGs. Therefore, it is necessary to study MG systems comprising multiple GFMs and SGs to understand the challenges that might arise in the parallel operation of different types of GFM DERs while supporting loads.

Most recent studies on the parallel operation of GFM inverters with SGs mostly focus on the analysis and evaluation of the transient stability of such MG systems. An electromagnetic transient study of a synthetic MG is conducted in [3] to investigate the droop coefficients of GFM inverters and SGs to maintain system stability under dynamic events. A decentralized virtual impedance scheme is studied in [4] to stabilize electric grids with GFM inverters and SGs with different GFM inverter penetration levels. Multiple GFM inverters in parallel with SGs are simulated for a real-world MG to study the steady-state and transient power sharing among them under different GFM inverter penetration levels in [5], and a field trial was conducted to validate the simulation results. A field demonstration with five virtual synchronous generator-based GFM inverters for a small MG is performed in [6] to showcase that the voltage and frequency control of the MGs are automatically regulated within a small bandwidth without any communication network; however, the system did not have an actual SG. The Consortium for Electric Reliability Technology Solutions (CERTS) microgrid concept demonstration at the Santa Rita Jail Microgrid also shows the parallel operation and automated power sharing of GFMs, GFLs, and SGs without any communication network [7].

Generally, GFMs with droop-based control can improve power sharing and the stability of the overall system. Most studies in the literature primarily highlight different challenges of the droop-based parallel operation of GFMs in simulation; however, it would be significantly challenging to implement similar controls on off-the-shelf, black-box GFM inverters with no access to control and limited access to settings (e.g., droop intercept and slope). Existing works also lack guidelines on how to characterize and properly configure GFM inverters for parallel operation. In addition, primary droop control allows GFM inverters and SGs to share power without communication; however, it is necessary to dispatch

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GFM inverters and/or SGs with the desired output power for better energy management. All these point to the need to develop a practical approach to dispatch off-the-shelf GFM inverters and SGs. With a deep understanding of droop control and our broad experience of operating GFM inverters and SGs, we propose dispatching GFM inverters and SGs in MGs with the desired output power by shifting the droop intercept up/down while maintaining the same frequency operating point because operating with the same frequency achieves better transient stability [8].

The main contributions of this paper can be summarized as follows: We 1) provide guidelines to characterize the droop curve and to configure and dispatch GFM inverters when GFM inverters are black box (with no access to inverter control); 2) design a practical analytical approach based on the droop curve to dispatch GFM inverters and SGs to achieve the target power output and maintain the MG system voltage and frequency stability; and 3) demonstrate the concept through a pure hardware setup with two off-the-shelf inverters and one diesel generator.

II. SYSTEM UNDER STUDY

This work is developed under the Universal Interoperability for Grid-forming Inverters Consortium (UNIFI) project, 1-MW multivendor GFM inverter demonstration [9]. Fig. 1 shows a simplified diagram of the Section 1 MG, which is selected for the demonstration. It includes a 250-kVA GFM inverter (Inverter 1), a 125-kVA GFM inverter (Inverter 2), and a 187.5-kVA diesel generator. Note that each GFM inverter needs a Δ-Y transformer to connect to other systems. Due to this transformer, the voltage droop of the GFM inverters is no longer accurate because of the reactive power consumed by the transformer; therefore, there is a need to characterize the droop of the GFM inverters (i.e., treat the inverter and the transformer as a whole) for parallel operation.

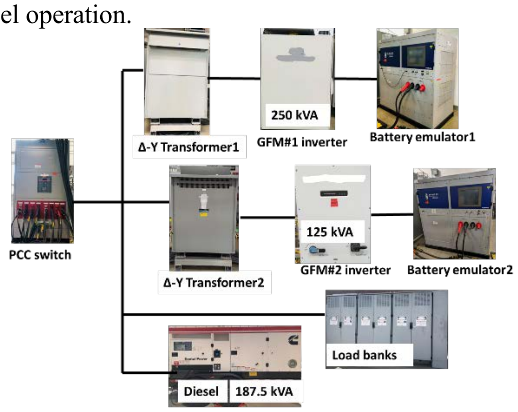


Fig. 1. Simplified diagram of the laboratory setup.

III. DROOP CHARACTERISTICS OF THE GFM SOURCES

A. GFM Inverter 1

Based on the user interface, the droop coefficients for frequency and voltage are 0.25% and 5%, respectively. Black-box testing is performed to collect data to verify the droop curves. For the frequency droop curve, we collect the following testing: power factor (PF) = 1 load equal to the capacity of the inverter, representing 5%, 10%, 25%, 50%, 75%, and 100% loading. For the voltage droop curve, we collect data on testing the inverter with pure inductive and capacitive load equal to the rated capacity of the inverter, representing 5%, 10%, 25%, 50%, 75%, and 100% loading. The data for the frequency droop confirm the droop coefficient, and the droop curve is $f^* = f_0 - mP$ ($f_0 = 1, m = 0.25\%$) on a per-unit (p.u.) basis. For the voltage droop, the data confirm that the voltage droop coefficient is incorrect, which requires characterization. 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 $v^* = v_0 - nQ$, 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.

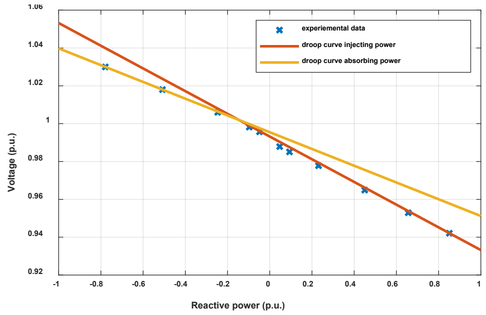


Fig. 2. Voltage droop characterization for Inverter 1.

B. GFM Inverter 2

The same procedure was performed for the second GFM inverter, but Inverter 2's reactive power capability is only between -1.2 and 0.5 p.u. From the user interface, the droop coefficients for the frequency and voltage are 0.83% and 5%, respectively. The same droop characterization testing is performed with this inverter. The 0.83% frequency droop coefficient is confirmed, and the voltage droop curve is shown in Fig. 3. Similarly, the positive and negative reactive power have different droop. For the positive reactive power, the droop curve is 1.0009-9.94%*Q, and it is 1.0027-7.1% for the negative reactive power.

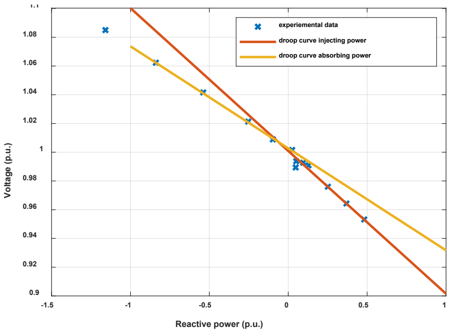


Fig. 3. Voltage droop characterization for Inverter 2.

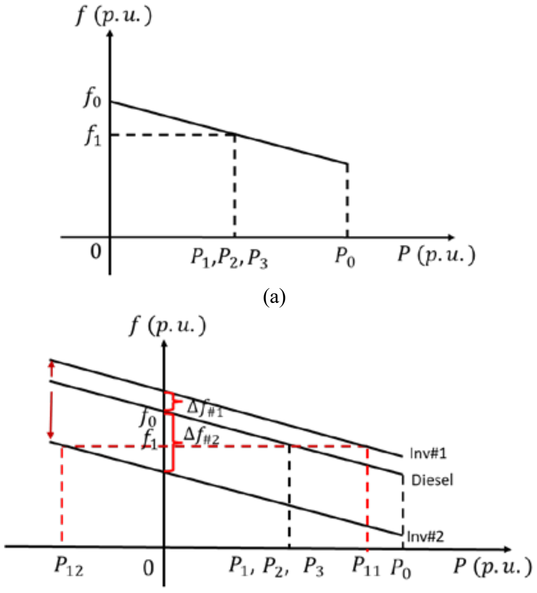
C. Diesel Generator

The diesel generator does not need a transformer, so there is no need to characterize its droop. Its droop parameters can be found in the front panel. The frequency droop is 0.6% with a bias of -0.36 Hz representing the droop intercept of "1," and the voltage droop is 3.7% with a zero-bias representing the droop intercept of "1." Note that the droop intercept is 0.6%*1*60 Hz because the diesel generator's frequency is 60 Hz while generates the rated active power.

IV. DROOP-BASED REAL-TIME DISAPTCH

For the GFL inverter, the real-time dispatch is straightforward, which usually sends active and reactive power set points to the inverter; however, it is not straightforward for the GFM inverter because the voltage frequency (VF) control does not directly control the active and reactive power and the GFM inverters automatically share the load based on the droop curve. To dispatch the GFM inverter to the desired active and reactive output power, the droop curve of each GFM inverter needs to be shifted/modified based on the desired output power. Theoretically, it is convenient to change the droop slope to achieve the desired output power; however, it might cause instability. Therefore, the preferred approach is to shift the droop intercept up/down to achieve the desired output power.

One example is given in Fig. 4. Fig. 4 (a) shows equal power sharing for Inverter 1, Inverter 2, and the diesel generator, and Fig. 4 (b) shows unequal power sharing among them, with Inverter 1 absorbing the desired active power. Fig. 4 (a) is suitable for the scenario in which the batteries of GFM inverter are fully charged, and Fig. 4 (b) is designed for the scenario in which one GFM inverter's battery needs to be charged because of a low state of charge. To be more generic, the droop curves are defined as: $f^* = f_0 - m_{1,2,3}P_{1,2,3}$, with m_1 and P_1 for Inverter 1, m_2 and P_2 for Inverter 2, and m_3 and P_3 for diesel. m and P are the frequency droop slope and the active power. f_0 is "1.0" for all three GFM sources. Because $m_1 = m_2 = m_3$, the three GFM sources output the same power in per unit. This can be a baseline operating point when all the GFM sources are fully charged with fuel/gas. To achieve unequal power sharing, as defined in Fig. 4 (b), from the baseline scenario (Inverter 2 absorbs power by P_{12}), it is better to keep the system frequency the same and to keep the diesel generator at the same operating point; therefore, Inverter 2 needs to shift the droop intercept down by $\Delta f_{\#2} = m_1(P_2 - P_{12})$, Inverter 1 needs to shift the droop intercept up by $\Delta f_{\#1} = m_1(P_{11} - P_1)$, and the diesel generator keeps the same droop curve and operating point. Because $m_1 = m_2, P_1 = P_2$ and $P_1 S_{Inv\#1} + P_2 S_{Inv\#2} = P_{11} S_{Inv\#1} + P_{12} S_{Inv\#2}$ (*P_{12}* is the desired output power and known), P_{11} and $\Delta f_{\#1}$ can be derived accordingly. The MG system controller only needs to dispatch the intercept to each inverter to achieve the target output.

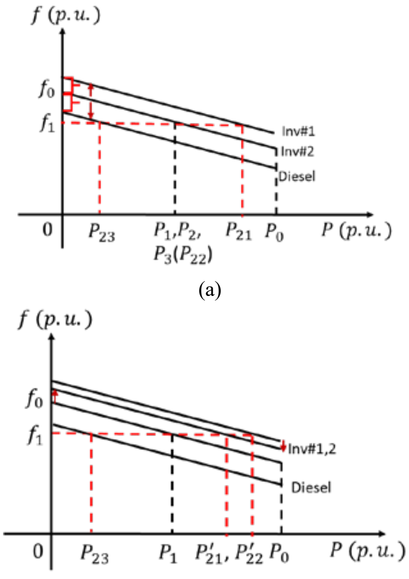


(a)

(b)

Fig. 4. Droop curve for multiple GFM inverters and the diesel generator: (a) equally sharing power on a per-unit basis; (b) unequally sharing power on a per-unit basis with one GFM inverter absorbing power.

Fig. 4 describes how the three GFM sources, which start from equal power sharing, change to unequal power sharing with a target power dispatched for the GFM inverters. To further validate the design concept, Fig. 5 shows a scenario in which the three GFM sources start from the baseline of equal power sharing, the diesel generator reduces power sharing because of the low fuel, and Inverter 1 takes over the discrepancy (Fig. 5 (a)), then two GFM inverters equally share power (Fig. 5 (b)). In Fig. 5 (a), the diesel generator reduces the power output to *P_{23}* by shifting the droop intercept down to $\Delta f = m(P_3 - P_{23})$, and Inverter 1 shifts the droop intercept up to $\Delta f = m(P_{21} - P_1)$. The power output for Inverter 1, Inverter 2, and the diesel generator are *P_{21}*, *P_{22}*, *P_{23}*, respectively, and the system frequency is *f_1*. Similarly, the intercept for Inverter 1 can be calculated accordingly, and the system controller dispatches the droop intercept to the diesel generator and Inverter 1 to achieve the target output power and system frequency. In Fig. 5 (b), Inverter 2 needs to shift up the droop intercept ($\Delta f = m(P'_{22} - P_{22})$), and Inverter 1 needs to shift down the intercept ($\Delta f = m(P_{21} - P'_{21})$) to equally share power and maintain the same system frequency. The system controller dispatches the droop intercept to achieve equal power sharing for the two GFM inverters. In general, the droop intercept to achieve the targe output can be derived as $\Delta f = m(P_{new} - P_{old})$, with P_{new} the new power output, and P_{old} the previous power output.



(a)

(b)

Fig. 5. Droop curve for multiple GFM inverters and the diesel generator: (a) unequally sharing power on a per-unit basis with less power from the diesel generator and Inverter 1 injects more power; (b) unequally sharing power on a per-unit basis with two GFM inverters equally sharing power.

V. SYSTEM CONFIGURATION

Table 1 summarizes the specifications of each element shown in Fig. 1. For our testing, we start with equal power sharing; thus, the three GFM sources are configured to have the same droop parameters, as shown in Table 1. In this work, we focus only on the active power dispatch, and the frequency droop slopes are configured the same. To reduce the reactive power flow between them, a shakedown test is performed to shift the voltage intercept of Inverter 1 by 2.3 V ($n * Q * 480$). For the real-time dispatch, a control algorithm of changing the frequency droop intercept is developed and implemented in a laptop to simultaneously dispatch the three GFM sources through Modbus TCP/IP.

Table 1. Components of the Section 1 MG Setup

Element	Capacity	Configuration/Feature
Inverter 1	250 kVA	Droop: 0.6% (f-P) and 6% (v-Q). Change f^* directly to shift the droop intercept.
Inverter 2	125 kVA	Droop: 0.6% (f-P) and 5.68% (v-Q). Change the bias (default is zero) to shift the droop intercept.
Diesel Generator	187.5 kVA	0.8 PF, 0.6% (f-P) and 6% (v-Q). Change the bias (default is -0.36 Hz) to shift the droop intercept.
Battery Emulator 1	±660 kW	DC voltage: 900 V; current: 306 A; power: 275 kW
Battery Emulator 2	±250 kW	DC voltage: 850 V; current: 162 A; power: 137.5 kW
Transformer 1	500 kVA	Delta: 480 V; wye: 480/277 V; current: 601 A, Z: 6%
PCC switch	1600 A	1600-A 4-pole circuit breaker
Transformer 2	250 kVA	Delta: 480 V, Wye: 480/277 V; current: 300A, Z: 4.4%
Load banks 1 and 2	250 kVA	2*250-kVA load banks in parallel 480 V, 3 phase

VI. EXPERIEMENTAL RESULTS

This section demonstrates the experimental results for the three GFM sources: Inverter 1, Inverter 2, and the diesel generator. We start from baseline scenario in which all three GFM sources equally share power on a per-unit basis. Then we demonstrate the scenario in which Inverter 2 needs to charge with the desired power, and Inverter 1 takes all the load from Inverter 1, and it also supplies power to Inverter 1. In the last scenario, the diesel generator needs to reduce the output power to a desired value, Inverter 1 takes all the shed load from the diesel generator, then Inverter 1 and Inverter 2 equally share power. Overall, we try to maintain the same frequency operating point for every test, which is essential to maintaining the system stability with multiple GFM sources. Note that only resistive load is applied for the experiment.

A. Baseline: GFM Sources Equaully Sharing Power on a Per-Unit Basis

To let all three GFM sources equally share power on a per-unit basis, the frequency droops are configured the same, 0.6%. This can be done in the inverter and the diesel GUI. Note that both Inverter 1 and the diesel generator use the droop slope in percentage, and Inverter 2 uses the frequency as the droop slope (e.g., 0.5 Hz stands for 0.83%). Because the test focuses only on the active power dispatch, we do not configure the reactive power droop slope assuming that all three GFM sources will not contribute reactive power. For this test, 0.4 p.u. (0.4*(250+125+150) resistive load is applied. The experimental results are shown in Fig. 6 and Fig. 7.

Fig. 6 shows the key measurements of all three GFM sources, including the voltage RMS, active and reactive power, and frequency. The three GFM sources can reach a common voltage near "1" p.u.; the three GFM sources have fluctuating active power, but the average level is 0.4 p.u.; approximately 0.05 p.u. reactive power flows from the diesel generator to Inverter 1, which indicates that the transformer Y-side voltage of Inverter 1 is still lower than the diesel generator, and Inverter 2 has near zero reactive power output; all three GFM sources have large oscillations in frequency but the average frequency of each GFM source stays at 59.86 Hz. The frequency and active power are coupled using droop control, which explains why both fluctuate. Overall, frequencies align with the theoretical calculation of 60-0.006*0.4*60.

Fig. 7 shows the longer duration and zoomed-in view of the output currents of the three GFM sources. Inverter 1 shows some oscillations, and the same for the diesel generator. The Inverter 2 output current shows a slight unbalance. Overall, the currents of the three GFM sources show clean sinusoidal waveforms with small distortions. Note that the voltages of the three GFM inverters exhibit no oscillations. Because of limited space, the results are not presented here. The voltage total harmonic distortion (THD) of the three GFM sources is less than 1%, the current THD of Inverter 1 is less 5%, and Inverter 2 and the diesel generator are slightly greater than 5%. The baseline test indicates that the three GFM sources can equally share active power, as expected, or the GFM sources can be dispatched to share equal active power through the same frequency droop.

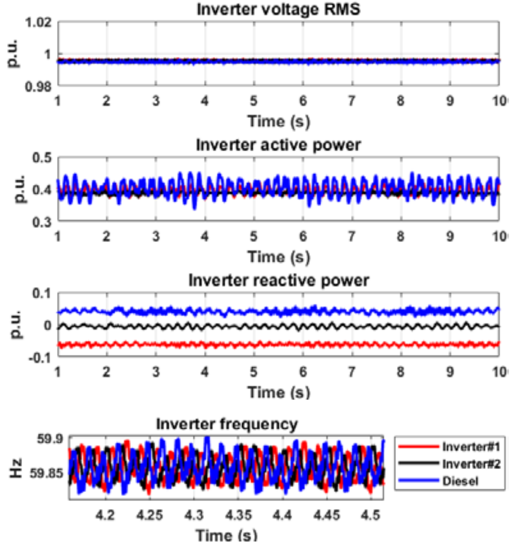


Fig. 6. Key measurements of the three GFM sources.

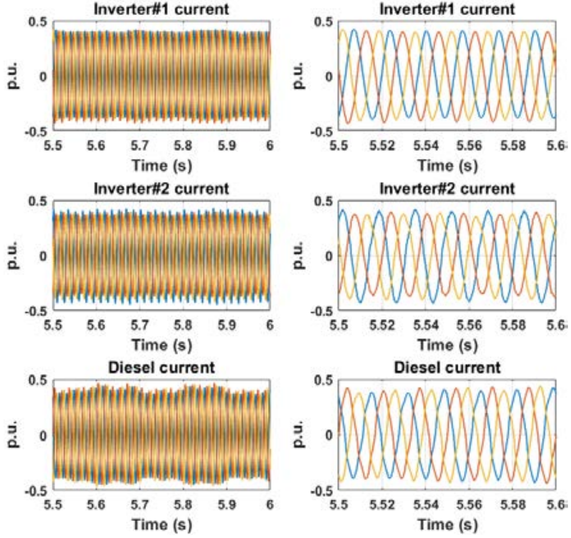


Fig. 7. Output current of the three GFM sources.

B. Dispatch the GFM Inverters with Inverter 1 Absorbing Desired Power

In this test, the goal is to dispatch one inverter (e.g., Inverter 2) to absorb the desired amount of power. To showcase this, the test can be performed by shifting the frequency droop intercept up/down, as explained in Fig. 3. For the testing, Inverter 2 is assigned to charge 0.4 p.u. power. Starting from the baseline scenario of equally sharing 0.4 p.u. active power, Inverter 2 absorbs 0.4 p.u. power, and the three GFM sources maintain the same frequency; Inverter 1 will pick up the load from Inverter 2 and supply Inverter 2, and the diesel generator will keep the same power output. Therefore, the frequency intercept of Inverter 2 needs to shift down by $\Delta f = 0.006 * (0.4 - (-0.4)) * 60 = 0.288$ Hz, and the frequency intercept of Inverter 1 needs to shift up by $\Delta f = 0.006 * (0.8 - 0.4) * 60 = 0.144$ Hz. Because this might cause instability with such a big frequency intercept shift for Inverter 1, we take two steps to complete the experiment; however, the precision of the frequency intercept is for only two decimals for both inverters. For example, Inverter 1 can take only 0.072 Hz instead of 0.07 Hz. Considering this limitation, the frequency intercepts for Step 1 are 59.84 Hz and 60.08 Hz for Inverter 2 and Inverter 1, and for Step 2 they are 59.7 Hz and 60.15 Hz. This dispatch results in Inverter 1's output power being near zero for the first step and near -0.4 for the second step.

Fig. 8 shows the key measurements of all three GFM sources, including the active power, frequency, voltage RMS, and reactive power. As shown in Fig. 8, Inverter 2's active power is near zero for the first step and reaches -0.42 p.u. for the second step; Inverter 1 increases its power to 0.61 p.u. for the first step and continues to increase its power to 0.81 p.u. for the second step; and the diesel generator maintains the same active power. The frequencies of all three GFM sources remain the same, and the change in the active power output of both inverters for each step affects the frequency of all three GFM sources. Overall, these results are expected. For the voltage, each GFM source slightly drops for each step, which can be understood because more power output causes more output current, and thus more voltage drop. The reactive power responses show an interesting phenomenon in which the reactive power flows from Inverter 2 to Inverter 1 because Inverter 2 has a higher terminal voltage after absorbing active power. Note that the response times for the two GFM inverters are spontaneous, and it is approximately 0.2 second for the diesel generator.

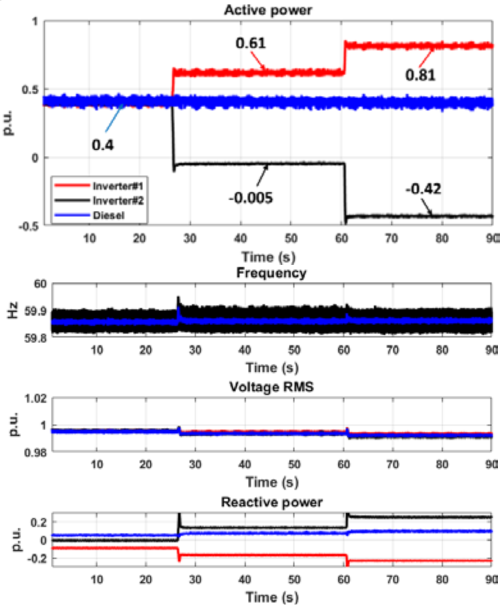


Fig. 8. Key measurements of the three GFM sources.

Fig. 9 shows the output currents of the three GFM sources for each step. In Step 1, both GFM inverters need approximately 1 second to reach steady state, and the diesel generator has the same output current. All three units show oscillations in their output currents. In Step 2, both inverters need less than 0.5 second to reach steady state. The THD level of this scenario is similar to the THD level in the baseline scenario. The output currents of the three GFM sources show the response of three GFM units achieving the target output power. Both Fig. 8 and Fig. 9 demonstrate the feasibility of dispatching the GFM active power output through the frequency droop intercept.

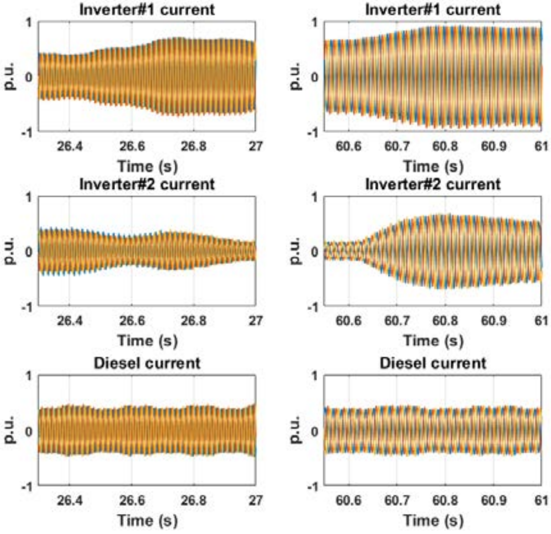


Fig. 9. Output current of three GFM sources for Step 1 (left) and Step 2 (right).

C. Dispatch the GFM Inverters with Desired and Reduced Power in the Diesel

In this test, the diesel generator is dispatched to reduce the active power of 0.4 (baseline) to 0.15 (the minimal loading constraint) to save fuel. For stability, only one GFM inverter is dispatched to take the shed load from the diesel generator (Step 1), and then two GFM inverters equally share power (Step 2). To achieve the goal, the frequency droop intercept of the diesel generator is shifted down by $\Delta f = 0.006 * (0.4 - 0.15) * 60 = 0.09$ Hz, and Inverter 1 needs to shift up the droop intercept by $\Delta f = 0.006 * (0.55 - 0.4) * 60 = 0.054 \approx 0.05$ $(0.4 + \frac{150}{250} * 0.25 = 0.55)$ in Step 1. In Step 2, Inverter 1's frequency droop intercept needs to shift down by 0.018 (≈0.02) Hz, and Inverter 2 needs to shift up by 0.036 (≈0.04) Hz so that the two GFM inverters can equally share power at 0.5 p.u. $(\frac{0.4*125+0.55*250}{250+125})$.

Fig. 10 shows key measurements of all three GFM sources, including the active power, frequency, voltage, and reactive power. In Step 1, the diesel generator gradually reduces its active power to a certain level (0.15 p.u. on average); Inverter 1 slowly generates more active power and reaches 0.51 p.u.; and Inverter 2 first reduces its output power and then gradually increases it to 0.4 p.u. prior to the event. In Step 2, Inverter 2 increases its active output power to 0.5 p.u., and Inverter 1 reduces its power to 0.47 p.u.. *The tracking errors are caused by rounding the droop intercepts into two-decimal precision (e.g., 0.054≈0.05)*. Because Step 1 involves a change in the diesel generator, which is a slow-response generation unit, its slow response affects the other two GFM inverters which are fast-response generation units. It took approximately 25 seconds to reach steady state in Step 1, whereas it is less than 0.1 seconds in Step 2. For the frequency responses, only Step 1 causes perturbations for the three GFM sources; Step 2 does not cause any transients in frequency. The steady-state frequencies are maintained to the value prior to the first change. For the voltage RMS, three GFM sources maintain similar voltage levels with unnoticeable drops for in both steps. More reactive power flows between the diesel generator and Inverter 1 because the diesel generator's terminal voltage increases with reduced power output, and the voltage at the Y-side of Inverter 1 drops with increased power output.

Fig. 11 shows the output currents of the three GFM sources for each step. In Step 1, Inverter 1 shows a slight increase in the output current, Inverter 2 has a reduced output current, the diesel generator's output current shows a slight decrease, and all three units need 25 seconds to reach steady state. In Step 2, Inverter 1 slightly reduces its output current, Inverter 2's output current increases, the diesel generator's output current is affected but quickly returns to normal, and all three units reach steady state within 0.1 second. The results show the oscillations in the currents of Inverter 1 and the diesel generator, which explains why the reactive power is exchanged between them.

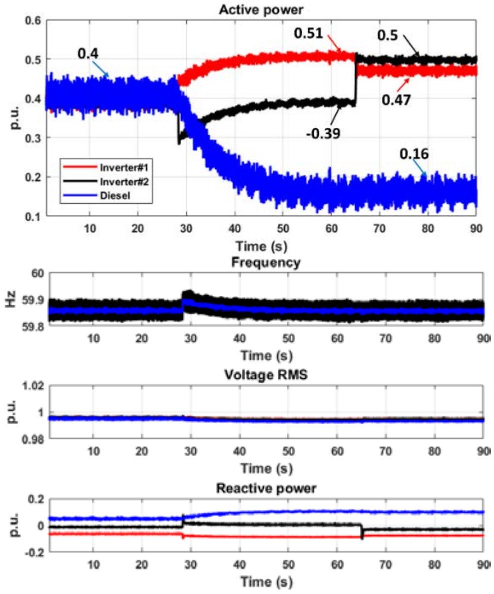


Fig. 10. Key RMS measurements of the three GFM sources.

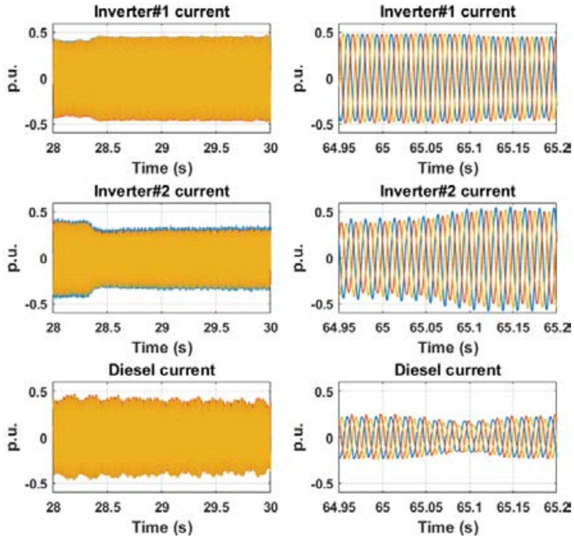


Fig. 11. Output current of three GFM sources in Step 1 (left) and Step 2 (right).

VII. DISCUSSION

These experiments successfully validate and demonstrate the concept of dispatching the active power output of the GFM sources in islanded MGs through frequency droop intercept. This work broadens the understanding of how GFM sources can work together and how to dispatch GFM sources, particularly GFM inverters' output power, like dispatching traditional GFL inverters. There is a duality between voltage and current; thus, the voltage and current can be controlled by each other, e.g., control the current to output the desired voltage. Similarly, there is a duality between frequency and active power (voltage and reactive power too), which is why there is droop and reversed droop, and one can control the other. With a deep understanding of these underlying principles and controls of GFM sources, controlling GFM sources' active power through frequency is a matter of fact. In addition, a few more insights are summarized as follows:

- It is important to compensate for voltage drop across transformer in the voltage droop equations to achieve expected reactive power sharing.
- Even though the concept is demonstrated in an islanded MG, the concept is applicable to grid-connected operation. Because the GFM inverter needs to comply with grid frequency (e.g., 60 Hz), then the desired output will be achieved by shifting the frequency intercept up/down by $\Delta f = m * P * 60$ to inject/absorb desired power (the output will be zero without shift).

VIII. CONCLUSION

This paper develops an analytical approach to dispatching off-the-shelf GFM inverters' active output power through frequency intercept. First, we characterize the GFM inverters' droop characteristics, which indicate that the frequency droop is accurate though the voltage droop is different from the set value. Then, an analytic study is performed to illustrate the principle of dispatching the GFM inverter's active power through frequency droop intercept. One case changes from equal power sharing to let one GFM inverter charge the battery, and the second case reduces the diesel output and then two GFM inverters equally share power. A pure hardware setup with 2 GFM inverters and one diesel generator is used to demonstrate the concept. The experimental results show that the dispatched GFM sources respond the changed droop intercept to output the desired active power, and it is important to maintain the same frequency. In the future, we will focus on grid-connected operation, and we will develop an algorithm to avoid overloading with unequal power sharing.

REFERENCES

[1] Research Roadmap on Grid-Forming Inverters. Available: https://www.nrel.gov/docs/fy21osti/73476.pdf.

[2] J. Wang, "Study of Inverter Control Strategies on the Stability of Microgrids Toward 100% Renewable Penetration," *IECON 2022 48th Annual Conference of the IEEE Industrial Electronics Society*.

[3] T. Zhang, "Impacts of Inverter Control Strategies on the Stability of Low-Inertia Power Systems," *IEEE Power and Energy Society General Meeting*, 2020.

[4] G. Raman, and G. Raman, "Inertia – Small-Signal Stability Nexus in Grid-forming Inverters," *2023 IEEE Power&Energy Society Innovative Smart Grid Technologies Conference (ISGT), 16-19 Jan. 2023*, Washington, DC, USA.

[5] Q. Lin, et al., "Field Demonstration of Parallel Operation of Virtual Synchrnous Controlled Grid-Forming Inverters and a Diesel Synchrnous Generator in a Microgrid," *IEEE Access*.

[6] Q.-C. Zhong, Y. Wang, and B. Ren, ''Connecting the home grid to the public grid: Field demonstration of virtual synchronous machines,'' *IEEE Power Electron. Mag.*, vol. 6, no. 4, pp. 41–49, Dec. 2019.

[7] E. Alegria, et al., "CERTS Microgrid Demonstration With Large-Scale Energy Storage and Renewable Generation," *IEEE Transactions on Smart Grid*, vol. 5, no. 2, pp. 937-943, March 2014.

[8] J. Wang, S. Ganguly, Benjamin Kroposki, "Study of Seamless Microgrid Transition Operation Using Grid-Forming Inverter," *IEEE IECON*, 2023 (Submitted).

[9] UNIFI project, Integration and Validation group presentation, available:https://research.csiro.au/ired2022/wpcontent/uploads/sites/477/2022/11/Unifi-Integration-and-Validation.pdf