Dispatching Grid-Forming Inverters in Grid-Connected and Islanded Mode

Preprint

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Dispatching Grid-Forming Inverters in Grid-Connected and Islanded Mode

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Abstract*—This paper explores the dispatchability of grid-forming (GFM) inverters in grid-connected and islanded mode. GFM inverters usually use droop control to automatically share power with other GFM sources (inverters and synchronous generators) and follow the change in the load demand; however, they can be dispatched like their grid-following (GFL) counterparts to output the target active and reactive power. This will help grid operators better manage their inverter-based resources (IBRs) to improve operation efficiency and reliability; therefore, this paper proposes an innovative concept of dispatching GFM sources (inverters and synchronous generators) to output the target power in both grid-connected and islanded mode by adjusting their droop intercepts. The fundamental principle is that the GFM inverter's active and reactive power is dictated by its frequency and voltage, and thus dispatching the active and reactve power of a GFM inverter can be achieved through dispatching its frequency and voltage. Moreover, the concept distinguishes the dispatch rules for grid-connected and islanded mode. Finally, the concept is validated with an example microgrid system with two GFM inverters, one diesel generator, one GFL inverter, and the load in both grid-connected and islanded mode. This pioneering work results in practical guidance for the development of energy management systems for future electric grids with GFM and GFL inverters.

I. Introduction

Many real-world projects and research and development studies have shown that inverter-based resource- (IBR-)dominant grids need grid-forming (GFM) IBRs to maintain power system stability and strength [1]. Many utilities have already installed GFM IBRs in their systems, including HECO, AMEO, ENTSO, etc., and increasingly more GFM inverters are being planned and will be installed in the near future; therefore, future power systems will include a mix of GFM and grid-following (GFL) IBRs with the accelerating retirement of fossil-fueled generators.

With the increasing need for GFM technology, many research works mainly focus on electromagnetic transient stability study to investigate how GFM inverter(s) can enhance system stability and strength. Also, the increasing penetration of GFM IBRs poses numerous challenges to the system-level control and dispatch of those IBRs, e.g., generation and load balance, voltage and frequency regulation. A net load management algorithm is developed in [2] to dispatch GFM and GFL inverters in an islanded microgrid to balance the generation and load while the GFM inverters share power based on the droop without additional dispatch. A decentralized distribution system restoration algorithm is developed in [3] using the coordination between GFM and GFL inverters with step-by-step procedures. A decentralized competitive power coordination scheme is developed in [4] to harmonize the GFM and GFL inverters to achieve both frequency recovery and active power distribution within the distribution network based on the Mean Field Games approach. An interesting work is developed in [5] to control the GFM and GFL inverters to ensure proportional power sharing as well as the regulation of the voltage and frequency with both the GFM and GFL inverters using droop control for their power loop. A unified droop-free distributed secondary control is developed in [6] based on distributed optimization to dispatch the GFM and GFL inverters to regulate the system frequency to the nominal value and the global average voltage to the rated value.

To date, there has been little research related to dispatching GFM and GFL inverters to meet the system-level objectives, but the system-level dispatch of GFM and GFL inverters is critical to achieving the system-level objectives, e.g., efficiency and reliability; therefore, this paper explores the dispatchability of GFM and GFL inverters to achieve the system-level dispatch goals. GFM inverters usually use droop control to automatically share power with other GFM sources (inverters and synchronous generators) and follow the change on the load demand [7]; however, they can be dispatched like their GFL counterparts to output the target active and reactive power [8]. This can help grid operators better manage the IBRs to improve power system operation efficiency and reliability. This paper proposes an innovative concept of dispatching GFM sources (inverters and synchronous generators) to output the target power in both grid-connected and islanded mode by adjusting the inverters' droop intercepts. The fundamental principle of doing so is that the GFM inverter's active and reactive power is dictated by its frequency and voltage, and thus dispatching the active and reactive power of a GFM inverter can be achieved through dispatching its frequency and voltage.

The main contributions of this paper can be summarized as follows: We 1) formulate the dispatch rule of GFM inverters in both grid-connected and islanded mode to achieve the system objectives (e.g., generation and load balance, voltage and frequency regulation); 2) demonstrate the concept through

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TABLE I
Specifications of the three GFM sources.

Specification	GFM 1	GFM 2	Diesel
Capacity (kVA)	250	125	187.5 (PF 0.8 lagging)
Frequency droop settings	0.25%	0.5 Hz	Bias of -0.36 Hz
Frequency droop	0.25%	0.83%	0.6%
Voltage droop settings	5%	24 V	Bias of 0%
Voltage droop	5%	5%	3.7%
Synch check	Yes (GCB and MCB)	No	Yes (GCB)
Operation mode	GFM, GFL, and grid-supporting control	GFL and GFM control	GFL and GFM control
Communication protocol	Modbus TCP	Modbus TCP	Modbus TCP

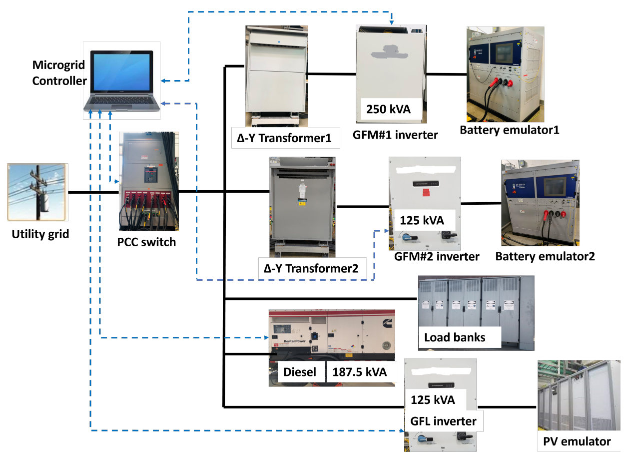

Fig. 1. Laboratory experiment setup.

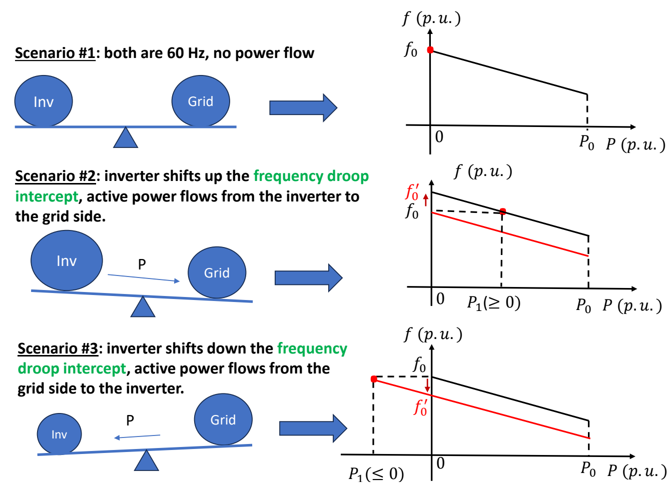

Fig. 2. Dispatch principle of grid-connected operation: equal frequency (top trace), the inverter frequency higher than the grid (middle trace), and the inverter frequency lower than the grid (bottom trace).

a pure hardware setup to have confidence in the efficacy of the proposed concept; and 3) develop the interoperability of the GFM and GFL inverters from the system level.; 4) This pioneering work results in practical guidance for the development of energy management systems (EMS) for the control of future electric grids with GFM and GFL inverters.

II. System Description

This work is performed as part of the UNIFI's consortium's 1-MW multivendor GFM inverter experiment, in which a microgrid system with four sections will be developed to evaluate the performance of multivendor GFM inverters (reference). Fig. 1 shows Section 1 of this microgrid, which is the system under study for this paper. This microgrid includes a utility grid (the main grid), a microgrid switch, two commercial GFM inverters (250 kVA and 125 kVA), one diesel generator (187.5 kVA, PF 0.8 lagging), one GFL inverter (125 kVA), and load banks (750 kVA). Each GFM inverter has a Δ-Y transformer connected, and the DC side is powered by a battery emulator. Table I shows the specifications of the GFM sources.

III. The Proposed Dispatch Algorithm for Grid-Connected and Islanded Mode

A. Grid-Connected Mode

In grid-connected mode, the grid voltage is dominant, so the GFM inverter must follow the grid voltage. Assuming that the grid frequency is 60 Hz, the inverter's operating point lands at zero active power and 60 Hz based on the droop curve, as shown in Fig. 2. When the inverter frequency droop intercept is shifted up, the active power flows from the GFM inverter to the grid. When the inverter frequency droop intercept is shifted down, the active power automatically flows from the grid to the GFM inverter. This autonomous response of the GFM inverter allows the system operator to dispatch the GFM inverter to output the target power. Fig. 2 illustrates the principles of the dispatch of the GFM inverter frequency droop intercept to allow the inverter to output the target active power when it is operated in parallel with the grid. Overall, the relationship between the target output active power and the adjustment of the frequency droop is described as:

$$f^* = 60 + \Delta f = 60 + m * P * 60 \qquad (1)$$

where m is the frequency droop slope, and P is the target active power in per unit (p.u.). In general, the active power output can be dispatched through adjusting the droop intercept.

B. Islanded Mode

In islanded mode, GFM sources usually use droop control to automatically share power with the droop settings based on the load and contribution from the GFL inverters. It is not straightforward to dispatch GFM inverters because the GFM voltage frequency (VF) control does not directly control the active and reactive power. To dispatch the GFM sources to the desired active and reactive power, the droop curve of each GFM inverter needs to be shifted/modified based on the desired output power. Theoretically, it is possible to change the droop slope to achieve the target output power, but this might cause instability; therefore, the suggested approach is to shift the droop intercept up/down to achieve the target output power, which is similar to the dispatch in grid-connected mode.

Using the microgrid system shown in Fig. 1 as the example, the islanded system includes GFM1, GFM2, diesel, a GFL inverter, and load (equal to 40% of the GFM source). The goal is to dispatch the GFM inverters to achieve the target power—e.g., charging GFM1's battery with 0.4 p.u. power from the baseline to have equal power sharing. Based on the capacity of each GFM source, GFM2 and the diesel would need to take additional power, $\Delta P = (0.4 - (-0.4)) * 250/(125 + 150) = 0.73$ p.u., but this will overload GFM2 and the diesel; therefore, the GFL inverter needs to take over some load from GFM2 and the diesel, which is $P_{min} = (0.73+0.4-1)*(125+150)/125 = 0.29$. p.u. To allow some headroom for GFM2 and the diesel, the GFL inverter is dispatched to output higher active power (e.g., 0.4 p.u.). Then, GFM2 and the diesel will output 0.95 p.u. active power if they share power equally. To achieve the planned dispatch, the following control references will be dispatched to the generation units: $\Delta f = (-0.4 - 0.4) * 0.006 * 60 = -0.288 \approx -0.29$Hz for GFM1 and $\Delta f = (0.95 - 0.4) * 0.006 * 60 = 0.2$Hz for GFM2 and the diesel. Based on our experience, the maximum allowable frequency droop intercept step cannot exceed 0.15 Hz; therefore, a few steps are taken to reach the target power output: 1) Shift the droop intercept of GFM1, GFM2, and the diesel to have GFM1 output 0% power and GFM2 and the diesel equally share the power drop by GFM1. 2) Dispatch the GFL inverter to output 0.4 p.u. power. 3) Shift the droop intercept of GFM1 to charge 0.4 p.u. power, and let GFM2 and the diesel provide power to support GFM1 charging. Fig. 3 illustrates the operating points of multiple GFM sources throughout the process. The generic rule of thumb to dispatch GFM sources for the target power output can be outlined as follows:

$$\Delta f = (P_{new} - P_{old}) * m * 60 \qquad (2)$$

where m is the frequency droop slope, P_{new} is the target active power in per unit, and P_{old} is the previous active power in per unit. This is how we dispatch the GFM inverter's output power by adjusting the droop intercept in islanded mode. Note that whenever GFL inverter contributes power, the system frequency operating point is shifted and the acitve power of GFM sources are different. Thus, the next dispatch must use the correct P_{old}.

C. Integrated Dispatch of GFM and GFL Inverters

Fig. 4 shows the schematics of integrating the dispatch of GFM and GFL inverters in both grid-connected and islanded mode. In grid-connected mode, the active and reactive power set points for the GFM and GFL inverters are generated based on the grid optimization algorithm with the control objectives and system and device constraints. Once the set points for the GFM inverters are generated, the GFM inverter can be dispatched to generate the target output power based on (1). One typical example can be a virtual power plant (VPP) where the microgrid is connected to the grid and dispatched to output the target power (e.g., zero active power).

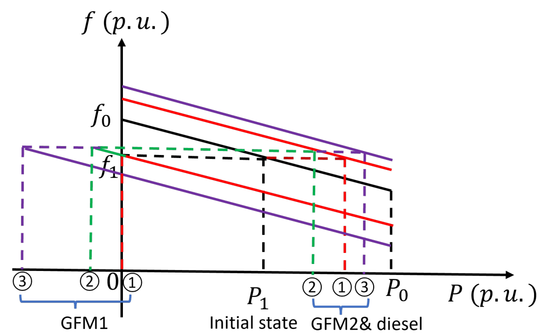

Fig. 3. Operating points of multiple GFM sources.

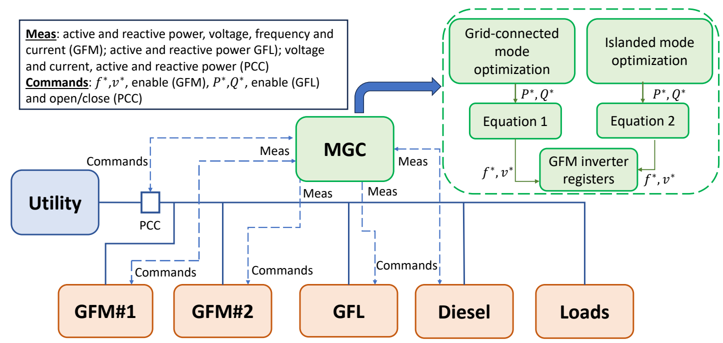

Fig. 4. Simplified schematic diagram of the integrated control system with the example microgrid.

In islanded mode, the generation and load balance is the most critical objective, apart from maintaining the voltage and frequency stability. It is common practice to have GFM sources equally share power based on the droop, and the GFL inverters are dispatched to supply additional load and keep some headroom for the GFM sources. As illustrated in Subsection B, it is possible to dispatch GFM inverters through adjusting the droop intercept to output the target power, like dispatching GFL inverters.

To integrate the dispatch of GFM and GFL inverters in both grid-connected and islanded mode, the generic framework shown in Fig. 4 can be used. Note that the main difference in dispatching GFM inverters in grid-connected and islanded mode is that the dispatch in grid-connected mode always refers to the baseline (60 Hz without shifting the droop intercept) for the next dispatch, as illustrated in eq. (1), whereas the dispatch in islanded mode always refers to the previous state for the next dispatch, as illustrated in eq. (2). Once the new droop intercept, f^*, is generated, it can be sent to the GFM inverter to output the target power. This diagram also shows the GFM inverter interoperability from the system operator's perspective. It is common sense that GFM inverters are dispatched through droop; and this work illustrates the dispatch rule of GFM inverters through droop.

IV. Experiment Results

To demonstrate the concept of dispatching GFM and GFL inverters in grid-connected and islanded mode, the laboratory

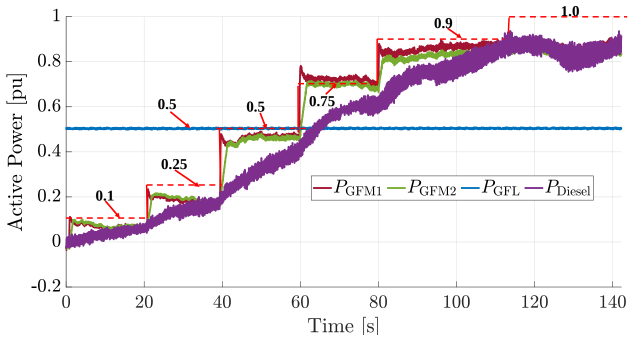

Fig. 5. Active power output of all generation units.

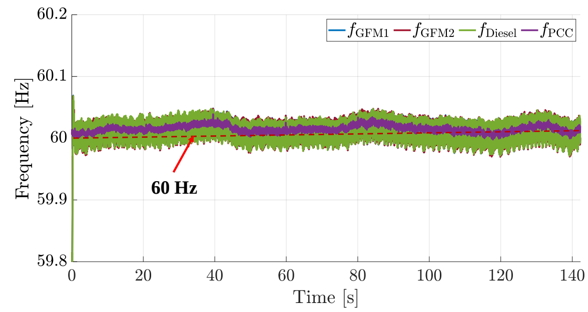

Fig. 6. Frequency of three GFM sources.

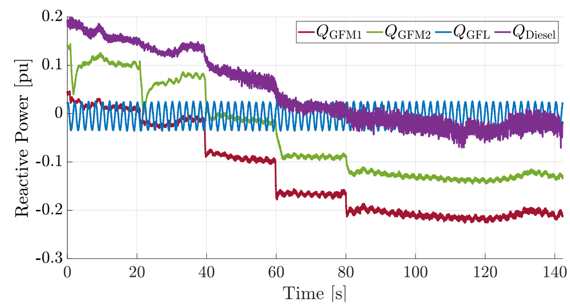

Fig. 7. Reactive power output of all generation units.

experiment is performed with the example microgrid system. In grid-connected mode, we aim to dispatch the GFM inverters and GFL inverters to supply all the load, and thus the power flow at the point of common coupling (PCC) is zero or minimized. In islanded mode, we demonstrate the scenario we presented in Section III.B. The testing results will be presented in the following subsections.

A. Grid-Connected Mode

The total load (unity power factor) equal to the sum of 100% of the total generation of the GFM capacity (250 kVA + 125 kVA + 150 kVA) and 50% of the GFL capacity (125 kVA) is set up. The GFL inverter is dispatched to supply load equal to 50% of its capacity, and the main grid supplies the rest of the load. All three GFM sources are generating zero power in the initial state. To achieve zero power at the PCC and demonstrate the concept, the three GFM sources generate power equal to 10%, 25%, 50%, 75%, 90%, and 100% of their capacity. The droop intercept of each GFM source needs to be shifted by 0.036 ($\approx$ 0.4), 0.09, 0.18, 0.27, 0.324 ($\approx$ 0.32), and 0.36 Hz, correspondingly, to achieve the target power. The experiment results are shown in Fig. 5 through Fig. 8. As shown in Fig. 5, the GFM sources try to generate the target power for all the operating points except the last one, the 100% dispatch scenario, and the GFL inverter outputs 50% power. The frequency of the three GFM sources and the utility grid are presented in Fig. 7. When the PCC frequency is at 60 Hz, GFM sources output the expected power (e.g., from 40 seconds to 120 seconds). While, when the frequency is higher than 60 Hz, the GFM sources output slightly lower power than the target ones. The reactive power of each generation unit is presented in Fig. 7. These results clearly show that the GFL outputs the target reactive power (zero), the diesel first injects reactive power and then stops the reactive power injection, GFM1 starts to absorb reactive power at the third dispatch, and GFM2 starts to absorb reactive power at the fourth dispatch. This can be understood that each GFM source's voltage decreases with more active power generation; therefore, the reactive power flows from the grid side to the GFM sources.

To further demonstrate the concept, the PCC active and reactive power are presented in Fig. 8. The PCC active power is gradually reduced with each dispatch and moves toward to zero with some steady-state error; however, the concept of dispatching the GFM inverters to the target power through the droop intercept is still validated, thus achieving the control objective of minimizing the active power at the PCC by dispatching the GFM sources and GFL inverter. This testing scenario verifies the concept that the GFM inverters can be dispatched through the droop intercept to output the target active power, and the GFM and GFL inverters can be dispatched to achieve the system objective (e.g., VPP).

B. Islanded Mode

The testing results in islanded mode are presented in Fig. 9 through Fig. 11. Note that the test starts from equal power sharing among the three GFM sources (0.4 p.u.), and the GFL outputs 0 p.u. active power. As shown in Fig. 9, GFM1 outputs the target active power: It outputs zero active power in the first step, it absorbs active power with the GFL inverter dispatching 40% output power in the second step, and it finally reaches the target power in the third step (absorbing 0.4 p.u.

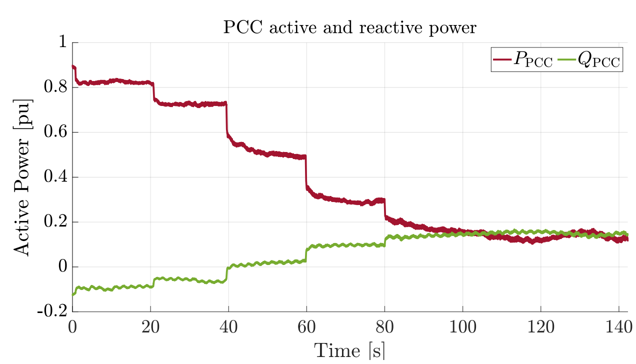

Fig. 8. PCC active and reactive power.

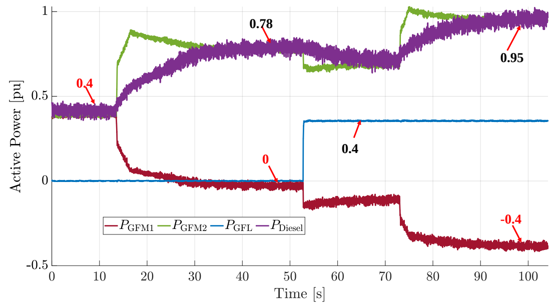

Fig. 9. Active power output of all generation units.

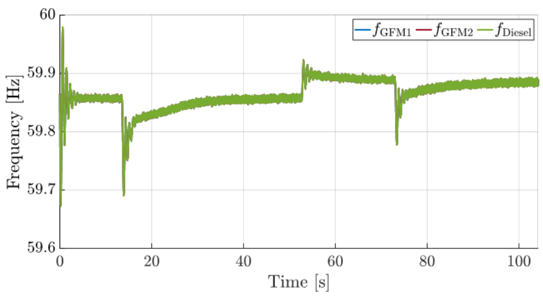

Fig. 10. Frequency of three GFM sources.

active power). Fig. 10 shows that the frequency exhibits an undershoot in the first step, slowly reaches steady state within less than 30 seconds, and maintains the same frequency prior to the step change; the frequency shows an overshoot in the second step and reaches steady state within 15 seconds, with a higher value than the previous step; and the frequency shows an undershoot in the third step, reaches steady state within 25 seconds, and maintains the same value prior to the step change. As expected, the GFM sources maintain the same frequency with the predefined droop intercept shift; however, the GFL inverter's contribute to shifting the operating frequency up because less power is contributed by GFM sources. Note that the system has better stability when the same frequency operating point is maintained. The reactive power output of each generation unit is shown in Fig. 11. Different from grid-connected mode, the reactive power of each generation unit is not that large. The diesel stops injecting reactive power and GFM2 starts absorbing reactive power at the third dispatch step. This can be understood by the fact that both GFM2 and the diesel need to inject more active power, which lowers their terminal voltage. Moreover, GFM1 starts to charge, which forces its terminal voltage to go up. The reactive power of the GFL is maintained at zero as expected. Overall, the testing results verify that GFM1 can be dispatched to output the target power by adjusting its frequency droop intercept.

V. Conclusion

This paper proposes the concept of dispatching GFM inverters with GFL inverters to achieve system-level objectives in both grid-connected and islanded mode. The concept is first illustrated through analysis and then validated through a full hardware setup with commercial GFM inverters, a GFL

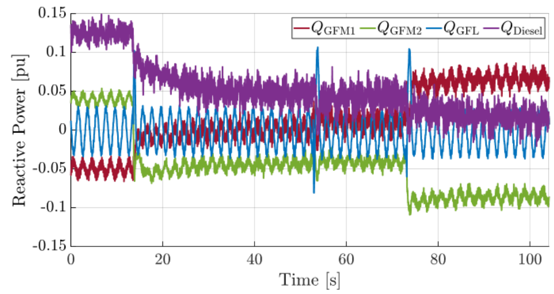

Fig. 11. Reactive power output of all generation units.

inverter, and a diesel generator. In grid-connected mode, the GFM inverters can be dispatched through the droop intercept to output the target power following the dispatch rule formulated in eq. (1). In islanded mode, the GFM inverters can also be dispatched through the droop intercept following the dispatch rule formulated in eq. (2). Moreover, the proposed dispatch rules in grid-connected and islanded mode can maintain system stability because they maintain the system frequency operating points. For a power system with fluctuating frequency (might not maintain 60 Hz all the time), the dispatch rule for GFM sources needs a small modification, which is to change the 60 Hz in eq. (1) as the grid frequency (f_{grid}). This can be achieved from a practical perspective because the grid operator always knows the frequency. Overall, the concept is demonstrated through the hardware experiment results with an example microgrid system, which develops pioneering work and gives direction for system EMS development to control future electric grids with GFM and GFL inverters. Future work will focus on dispatching both the active and reactive power of GFM inverters through adjusting the droop intercepts.

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