Study of Seamless Microgrid Transition Operation Using Grid-Forming Inverters

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Study of Seamless Microgrid Transition Operation Using Grid-Forming Inverters

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***Abstract*—This paper investigates operational techniques to achieve seamless (smooth) microgrid (MG) transitions by dispatching a grid-forming (GFM) inverter. In traditional approaches, the GFM inverter must switch between grid-following (GFL) and GFM control modes during MG transition operation. Today's inverter technology allows GFM inverters to always operate in GFM control mode, so it is worth exploring how to use them to achieve smooth MG transition operation. This paper proposes three operational techniques: a traditional scheme of switching between GFL and GFM control; a new scheme of consistent GFM control and shifting the droop intercept up before islanding operation; and a new scheme of consistent GFM control and shifting the droop intercept up before synchronization operation. A full hardware setup is established to compare the three techniques and showcase their implementations in real-world applications. The results show that the third technique outperforms the others and exhibits the best transition performance because the GFM inverter maintains the same operating points during the transition operation. Therefore, we conclude that ensuring smooth MG transition operation requires that the GFM inverter(s) maintain the same operating points (v, f, P, Q, and phase angle) during the transition operation in addition to minimizes the point of common coupling power flow.**

Keywords—Grid-forming control, islanding operation, smooth transition operation, synchronization operation.

I. INTRODUCTION

Grid-forming (GFM) inverters have been widely used in microgrid (MG) applications to form the local system voltage when there is a loss of the main grid to enhance local customer reliability. [1]. To achieve this, the MG controller must have the capability to perform a transition of operation between grid-connected and islanded mode. Making this transition without impacting the local load operation is called a "seamless" or "smooth" transition. This transition capability is of great importance, especially with the accelerated integration of distributed energy resources (DERs) [2]. IEEE Std. 2030.7 mandates that the transition function and the dispatch function must be designed into the MG controller. The transition operation usually involves coordination among the MG, the point of common coupling (PCC) relay, and the GFM sources (e.g., GFM inverters) [3]. In particular, the GFM inverter is the key enabler to achieve seamless transition operation because the controls embedded in the inverter are able to maintain a somewhat stable voltage and frequency at the PCC during MG transition operation.

A generalized GFM control algorithm is developed in prior work [4] to achieve a smooth MG transition operation by designing a voltage control mode with a closed-loop transfer function equal to the "unity gain," thus cancelling out all the disturbances seen by the inverter, especially during MG transition operation. Similarly, an improved droop-based voltage control mode has been developed to reject the disturbances associated with the MG transition operation and to emulate the inertial response of a synchronous generator, thus suppressing voltage, current, and frequency fluctuations to guarantee smooth transition [5]. A control design similar to [4] is developed in [6] to achieve the closed-loop transfer function equal to unitary, thus rejecting all the disturbances seen by the controller and achieving a smooth transition operation. A control strategy developed for synchronization operation to ensure that the PCC status is communicated to the inverters to change the operation mode is given in [7] and [8]. Some additional control strategies have focused on keeping a consistent phase angle for the GFM inverter during transition operation, such as integrated synchronization control in the GFM inverter for MG islanding and synchronization operation are provided in [9].

Startup and MG synchronization operation [10], and modified droop control for both grid-connected and islanded mode [11] have been developed. A MG control method is shown in [12] to minimize the power flow at the PCC, and an islanding master (a microturbine) is selected to form the system voltage after islanding operation. Lessons learned from a real-world MG project indicate that successful transition operation is achieved because of properly designed transition sequences and control strategies (that minimize the power flow at the PCC) [13].

Although extensive work has been done to address the challenges associated with MG transition operation from different angles (GFM control, GFM phase angle control, and MG control and coordination), many questions remain regarding how the seamless transition operation of MGs really works, especially from a real-world perspective. In addition,

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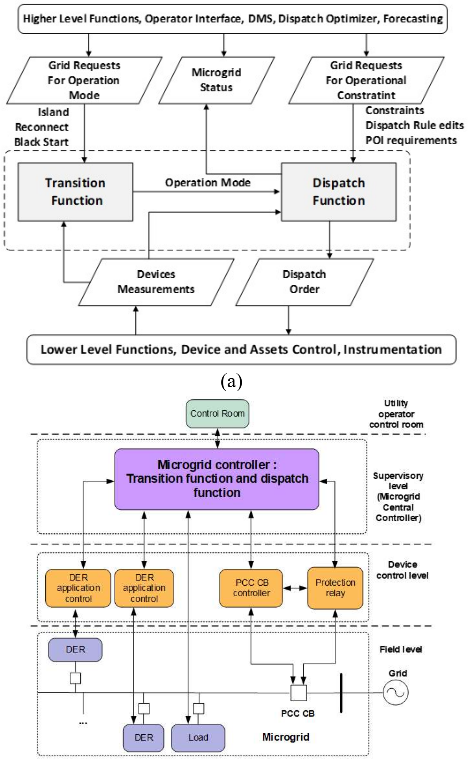
since today's GFM inverters can consistently operate in GFM control mode, it is useful to examine how to ensure smooth transtions between grid-connected and islanded modes. Therefore, this paper goes beyond the current state of the art and explores smooth MG transition operation strategies with a focus on exploring using GFM inverters that are always in GFM control mode and how to dispatch them for smooth transition operation. The main contributions of this paper can be summarized as follows: We 1) design three operational techniques to achieve smooth MG transition operation, including a traditional scheme of switching between Real Power and Reactive Power (PQ) and Voltage-Frequency (VF) control; a new scheme of consistent GFM control and shifting the droop intercept up before islanding operation; and a new scheme of consistent GFM control and shifting the droop intercept up before synchronization operation; 2) establishing a MG setup and demonstrating the three proposed schemes through experiments to showcase the real-world applications; and 3) concluding that ensuring smooth MG transition operation requires the GFM inverter(s) to maintain the same operating points (v, f, P, Q, and phase angle) during the transition operation, which also minimizes the PCC power flow.

II. DESCRIPTION OF THE MICROGRID CONTROL SYSTEM

A. The Microgrid Control System

Fig. 1 shows a high-level representation of the MG control system, with Fig. 1 (a) focusing on the system control function blocks per IEEE Std. 2030.7 [3] and Fig. 1 (b) focusing on the system control architecture reflecting real-world applications. As indicated in Fig. 1, the transition function in the MG controller receives the grid request for the operation mode and devices measurements (e.g., PCC status) to decide the operation mode and directs the dispatch function to dispatch the grid assets.



(a)

(b)

Fig. 1. High-level represntation of the MG system for transition operation: (a) IEEE Std. 2030.7; (b) MG control architecture.

B. The Interoperability for Transition Operation

The transition operation mainly involves the MG controller, the PCC relay and circuit breaker, and the GFM inverters. Note that the PCC relay manages the opening and closing of the PCC circuit breaker. During a planned island condition, when the transition operation request is received from the grid operator, the MG controller tries to minimize the power flow at the PCC to avoid any harmful transients, and it also issues the transition operation command to the PCC relay and the GFM inverters. For synchronization operation, the GFM inverter(s) adjusts its voltage and frequency to ensure that the voltages at the MG and the main grid stay close to each other, and the PCC relay will close the PCC circuit breaker if the differences between the two voltages' magnitude, frequency, and phase angle are within the thresholds. Normally for islanding operation, the GFM inverter(s) will automatically switch from grid-following (GFL) control to GFM control, and the PCC relay will open the PCC circuit breaker if the power flow is close to zero.

III. TECHNIQUES FOR SMOOTH MICROGRID TRANSITION OPERATION

With advances in GFM inverter technology, commercial, off-the-shelf GFM inverters can be configured to operate in GFM control while in grid-connected mode; therefore, there are more ways to dispatch the GFM inverter for a smooth MG transition operation. Based on our experience, there are three ways to achieve smooth MG transition operation: 1) switch between GFL and GFM control based on the PCC circuit breaker status (traditional); 2) always use GFM control with the frequency droop intercept shifting up to minimize the imported/exported power from the grid *before islanding operation*; and 3) always use GFM control with the frequency droop intercept shifting up to minimize the imported/exported power from the grid *before synchronization operation*. Overall, each scheme needs to minimize the PCC power flow during the transition operation to minimize the disturbance that occurs from opening the PCC breaker. Each method is explained in detail in this section, and the transition operation includes synchronization and islanding operations.

A. Transition Operation: Scheme 1

For this traditional scheme, the active and reactive power references (usually equal to the actual power output before synchronization) are dispatched before the synchronization operation so that the GFM inverter outputs the dispatched power when the MG transitions to grid-connected mode. The GFL inverters are dispatched to generate the same power during synchronization operation; therefore, the GFM inverters output the same amount of power during synchronization operation. Similarly, voltage and frequency references (usually equal to nominal values) are dispatched before the islanding operation, and the GFM inverters are dispatched to generate the same power during islanding operation. At the same time, the power flow at PCC needs to be minimized.

B. Transition Operation: Scheme 2

In this scheme, the GFM inverter always operates in GFM control mode. Fig. 2 describes the operating trajectory of the GFM inverter during the transition operation, including islanded mode and synchronization operation (S_0), grid-connected mode (S_1), and islanding operation and islanded mode (S_2). In islanded mode and synchronization, the GFM inverter operates in droop control, and the operating point is f_1 and P_1. When the PCC circuit breaker is closed (grid-connected mode), the GFM inverter automatically shifts to S_1, where its active power output is zero and the frequency is nominal (f_0) based on the droop because the main grid is dominant, with a nominal frequency, and the GFM inverter must reach nominal frequency to achieve stability and a steady state. For islanding operation, the GFM inverter is dispatched to output the desired amount of power (e.g., P_1) to take all the imported power from the grid, then the droop is shifted up by $\Delta f = m * P_1 * 60$ (m is the frequency droop slope). The GFM inverter operating points are P_1 and f_0. Once the PCC circuit breaker is open, the GFM inverter continues to operate at S_2.

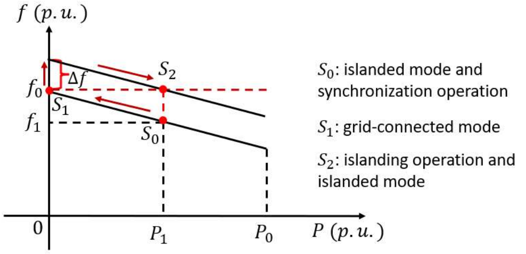


Fig. 2. Operating points of Scheme 2.

C. *Transition Operation: Scheme 3*

This scheme is similar to Scheme 2, but the difference is that it shifts the frequency droop intercept up before the synchronization operation, so the GFM inverter already outputs the nominal frequency with the same power output before the PCC circuit breaker is closed. Fig. 3 describes the operating trajectory of the GFM inverter during the transition operation, including islanded mode (S_0), synchronization operation, grid-connected mode, and islanding operation and islanded mode (S_1). Before synchronization operation, the frequency intercept is shifted up by $\Delta f = m * P_1 * 60$, which changes the operation points of the GFM inverter from S_0 to S_1. Because the GFM inverter has a frequency equal to the nominal (the grid frequency), it might take longer to close the PCC circuit breaker because the phase angle difference needs more time to reach the threshold. On the other hand, this will enable smoother synchronization because the frequency is equal to the grid frequency. Once the PCC circuit breaker is closed, the GFM inverter still operates at S_1, and the same for islanding operation and islanded mode. That said, shifting the frequency droop intercept up before the synchronization operation is the only operation needed during the whole transition operation. Overall, this scheme is expected to have the best transition operation because the inverter always operates at the same operating points (nominal frequency), which reduces the inverter's transients and minimizes the interaction with the grid.

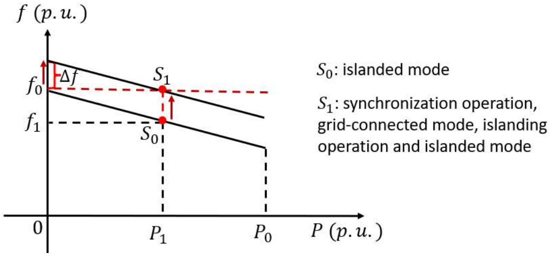


Fig. 3. Operating points of Scheme 3.

IV. MICROGRID SYSTEM UNDER STUDY

To validate and demonstrate the three proposed transition operation schemes, a hardware setup of a simple MG is developed in the laboratory. The setup is depicted in Fig. 4. The specification for each element is listed in Table 1.

The MG controller is a computer to dispatch the GFM inverter and issue the synchronization and islanding request to the PCC relay. This MG controller communicates with the inverter and the PCC relay through ModBus TCP/IP. Note that the PCC status is fed into the GFM inverter to transition between PQ and VF control based on the MG operation status in Scheme 1; however, this signal is bypassed in the experiment, and the PCC status is hard-coded to be "0" so that the GFM inverter always operates in GFM control mode in Scheme 2 and Scheme 3.

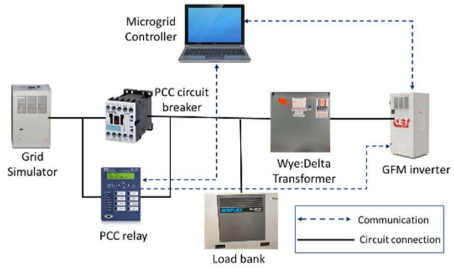


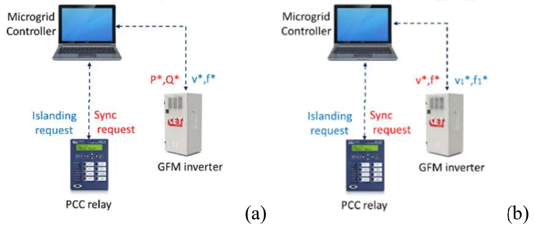
Fig. 4. A simplified diagram of the laboratory MG setup.

Table 1. Components of the MG Setup

Element	Capacity	Configuration/feature
Grid simulator	45 kVA	Internal voltage reference (60 Hz and 277 V)
PCC circuit breaker	111.9 kW	150HP, 3 Phase Contactor
PCC relay	n/a	$\Delta\vartheta$: 3°, Δv: 0.03 p.u., Δf: 0.02 Hz
Transformer	75 kVA	Delta:480V, Wye:480/277V, Current: 90A, Z: 4.4%
Inverter	30 kVA	Droop: 0.64% (f-P) and 6.8% (v-Q)
Load bank	100-kVA RL load	15-kW R load

V. EXPERIEMENTAL RESULTS

This section demonstrates the experimental results for the three transition operation schemes. For the testing, the operation sequence is performed as follows: The GFM inverter black-starts itself and the transformer, and then the load bank, set at 15 kW (50% of the GFM inverter capacity), is connected to the inverter; the dispatch and synchronization request is performed in the MG controller; the relay closes the PCC circuit breaker and the MG goes to grid-connected mode; the dispatch and islanding request is performed in the MG controller; and the relay opens the PCC circuit breaker and the MG goes to islanded mode. Fig. 5 shows the dispatch for the three transition operation schemes. Red indicates synchronization operation, and blue is for islanding operation. The results include synchronization and islanding operation.



(a) (b)

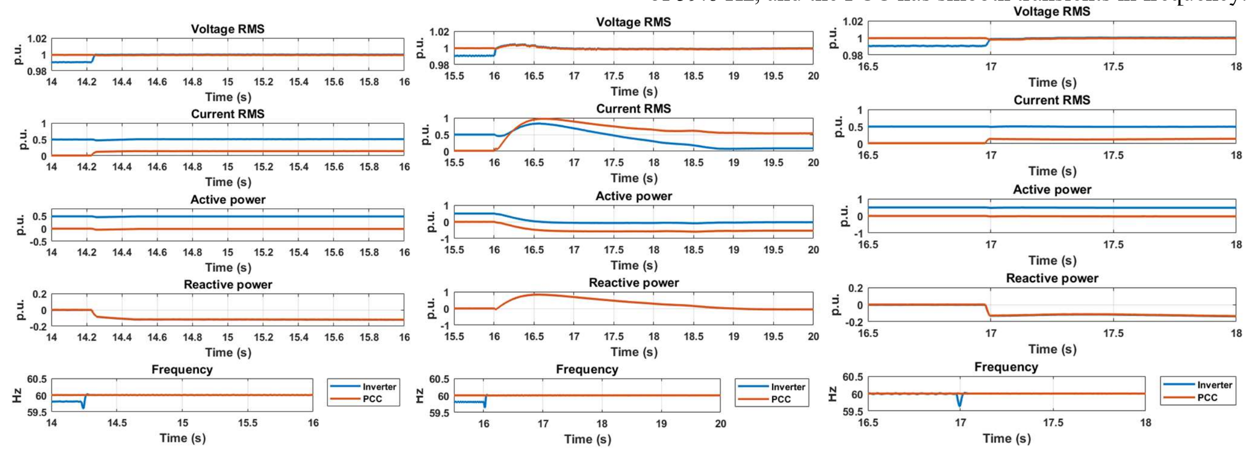
(c)

Fig. 5. Disaptch for the three transition operation schemes: (a) Scheme 1; (b) Scheme 2; and (c) Scheme 3.

A. Synchronization Operation

In Scheme 1, P^* and Q^* are 15 kW and 0 Var, which are dispatched before the synchronization request, and the inverter will switch from GFM control to GFL control when the PCC circuit breaker is closed. In Scheme 2, v^* and f^* are maintained the same (nominal), and the inverter always operates in GFM control mode. In Scheme 3, the droop intercepts are shifted up to let the inverter take the same load after the PCC circuit breaker is closed, and the v^* and f^* are shifted up by $n * Q * 480$ V $(Q \approx 0)$ and $m * P * 60$ $(P \approx 0.5)$ Hz, respectively. The new voltage and frequency references are v_1^* and f_1^*. The testing results for the three schemes are presented in Fig. 6 and Fig. 7.

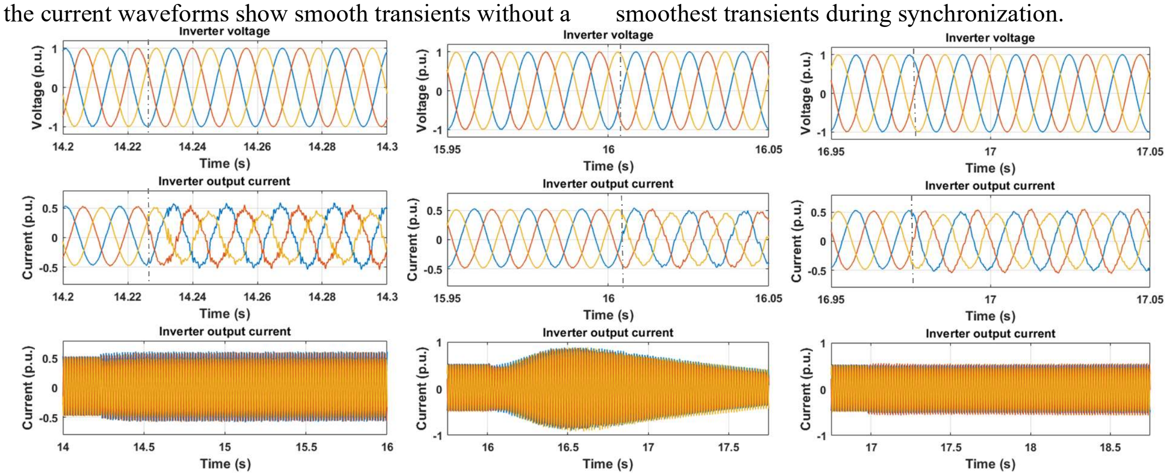
Fig. 6 shows the key measurements of the inverter and the PCC during synchronization for the three schemes. In Scheme 1, the inverter outputs the same amount of power, and the PCC power flow is maintained close to "zero" before and after the PCC circuit breaker is opened; thus, both the inverter and the PCC have very smooth transients in voltage, current, and active and reactive power. The inverter has frequency nadir of 59.6 Hz in frequency, and the PCC frequency is very smooth. In Scheme 2, the inverter's output active and reactive power go to zero because the grid simulator is the dominant source, with the voltage and frequency equal to the nominal values, and the inverter's voltage and frequency operating points are at the intercept (nominal), as shown in Fig. 2. With the big change in the inverter's operating points and an increased power flow at the PCC, both the inverter and the PCC indicate transients. The inverter has a frequency nadir of 59.6 Hz, and the PCC's frequency still doesn't show any transients. In Scheme 3, the inverter is expected to output the same power before and after the PCC circuit breaker is opened (as shown in Fig. 3); however, the inverter absorbs a small amount of reactive power (0.18 p.u.) because the inverter terminal voltage is less than the PCC voltage. Thus, the inverter and the PCC have smooth transients. The inverter has frequency nadir of 59.6 Hz, and the PCC has smooth transients in frequency.



(a) (b) (c)

Fig. 6. Measurements of the inverter and the PCC during synchronization: (a) Scheme 1; (b) Scheme 2; and (c) Scheme 3.

Fig. 7 shows an expanded view of the voltage and current waveforms of the three schemes during synchronization. For all three schemes, the voltage waveforms show no transients, and the current waveforms show smooth transients without a phase jump during synchronization. The settling time is 0.3 second in Scheme 1, 3.5 seconds in Scheme 2, and 0.032 second (2 cycles) in Scheme 3; therefore, Scheme 3 has the smoothest transients during synchronization.



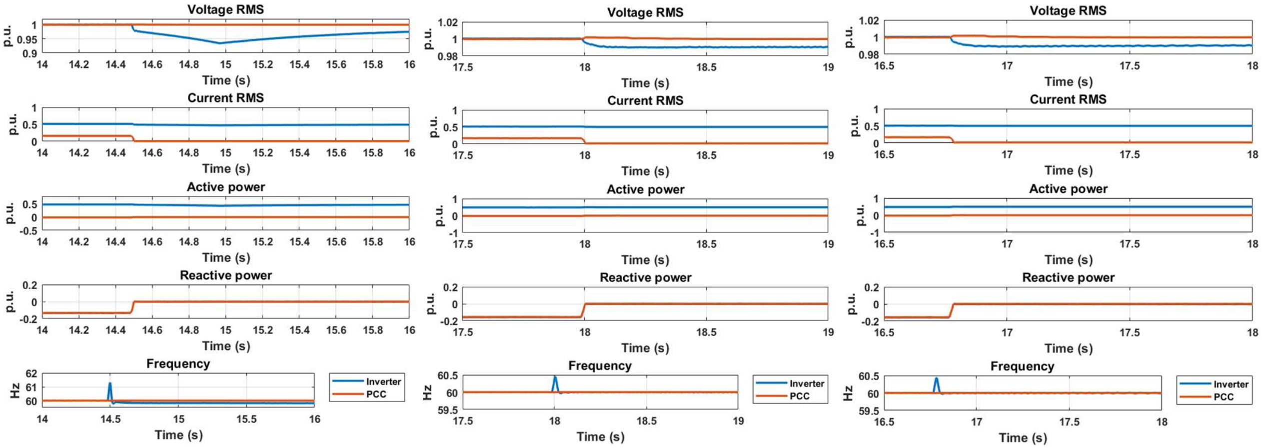
(a) (b) (c)

Fig. 7. Zoom-ed in view of the votlage and current sinosoidal waveforms during synchronization: (a) Scheme 1; (b) Scheme 2; and (c) Scheme 3.

B. Islanding Operation

In Scheme 1, v^* and f^* are equal to the nominal value, which are dispatched before the islanding request, and the inverter will switch from GFL control to GFM control when the PCC circuit breaker is open. In Scheme 2, the droop intercepts are shifted up to let the inverter take the same load after the PCC circuit breaker is open, and v^* and f^* are shifted up by $n * Q * 480$ V ($Q \approx 0$) and $m * P * 60$ ($P \approx 0.5$) Hz, respectively. The new voltage and frequency references are v_I^* and f_I^*. In Scheme 3, the voltage and frequency references are maintained the same (v_I^* and f_I^*), with the inverter always operating in GFM control mode. No additional operation/dispatch is needed in Scheme 3. The testing results for the three schemes are presented in Fig. 8 and Fig. 9.

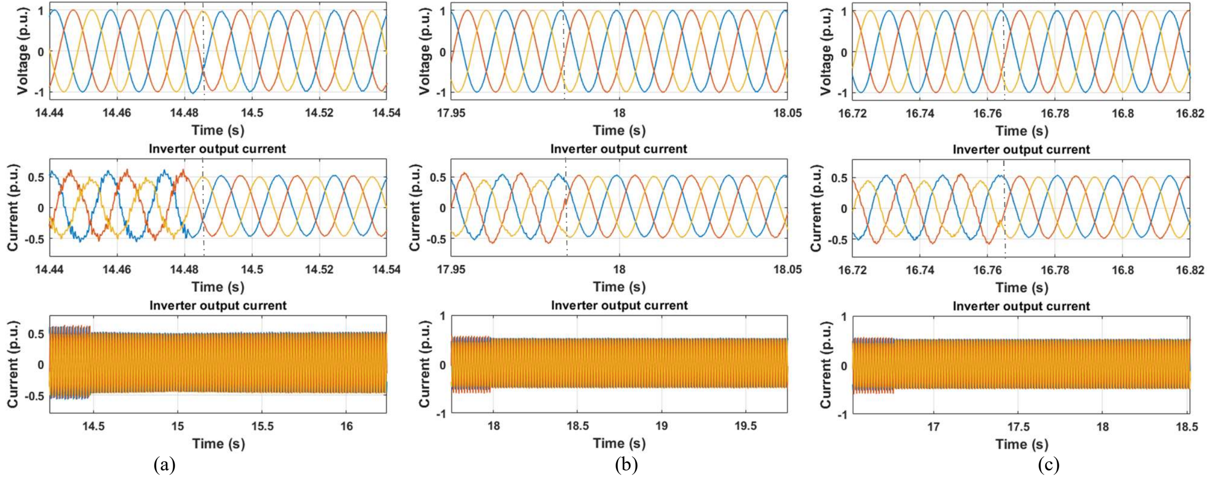
Fig. 8 shows the key measurements of the inverter and the PCC during islanding for the three schemes. In Scheme 1, the inverter outputs nearly the same amount of power (slightly increased reactive power), and the PCC power flow is maintained close to "zero" before the PCC circuit breaker is open; thus, both the inverter and the PCC have very smooth transients in voltage, current, and active and reactive power. However, the inverter has a noticeable drop in voltage when the PCC circuit breaker is open, its voltage continues to drop to its lowest point (0.92 p.u.), and then it ramps up to a steady state. The inverter's frequency has an overshoot of 61.2 Hz, and the PCC frequency has negligible transients. The inverter has similar transients in voltage, current, and active and reactive power in Scheme 2 and Scheme 3 because the inverter has the same operating points for these two schemes during grid-connected operation, as shown in Fig. 5, and the inverter does not change the operating points during islanding operation for both schemes. This ensures smooth transition operation for the inverter. The inverter and the PCC have smooth transients for the voltage, current, and active and reactive power; the inverter's frequency has an overshoot of 60.5 Hz; and the PCC has no overshoot or undershoot in frequency.



(a) (b) (c)

Fig. 8. Measurements of the inverter and the PCC during islanding operation: (a) Scheme 1; (b) Scheme 2; and (c) Scheme 3.

Fig. 9 shows an expanded view of the voltage and current waveforms of the three schemes during islanding. For all three schemes, the current waveforms show no transients during islanding. The voltage in Scheme 2 and Scheme 3 shows no transients, and there is a very small transient for the voltage in Scheme 1. In Scheme 1, even though the inverter needs to switch from PQ control to VF control during islanding, there is no phase jump in the inverter voltage and current. The settling time after islanding is 2 seconds in Scheme 1 and 0.032 second (2 cycles) in Scheme 2 and Scheme 3; therefore, Scheme 2 and Scheme 3 have better islanding transition performance.



(a) (b) (c)

Fig. 9. Zoom-ed in view of the votlage and current sinosoidal waveforms during islanding: (a) Scheme 1; (b) Scheme 2; and (c) Scheme 3.

VI. DISCUSSION

This paper presents three innovative operational approaches to achieve smooth MG transition operation by using the latest GFM inverter technology. Even though a small MG setup is used to validate and demonstrate the three schemes, the concept is applicable to MG systems with multiple GFM inverters and GFL inverters. The key idea is to have the GFM inverters have the same operating points during the MG transition operation (also for the GFL inverters). Moreover, this is greatly helpful for unplanned islanding operation because the GFM inverters shift along with the droop curve before and after the PCC circuit breaker is opened, which is still considered to have fewer changes in operation points than the traditional method of switching between GFL and GFM control.

In addition, configurating the GFM inverter to always be in GFM control mode also avoids the delays from sending the PCC status to the inverter and switching between control modes. That's why the traditional method of switching from GFL to GFM control during islanding operation takes longer to establish and sustain the system voltage for islanded MGs. Based in the experiments, Scheme 3 has the best transition operation performance because the inverter maintains the same operating points (v, f, P, Q, and phase angle) during the transition operation. This guarantees that there are no/small transients during the MG transition operation. The operation sequence of transition operation demonstrated in this paper starts from islanded MG, however, the idea is still applicable if the MG starts from grid-connected mode. Before islanding operation, the droop intercepts need to be shifted up to generate the power which is equal to the islanded mode.

VII. CONCLUSION

Transition operation is a critical function for MGs. This paper proposes three operational techniques to achieve smooth MG transition operation: the traditional scheme of switching between GFL and GFM control (Scheme 1); a new scheme of consistent GFM control and shifting the droop intercept up before islanding operation (Scheme 2); and a new scheme of consistent GFM control and shifting the droop intercept up before synchronization operation (Scheme 3). A small MG setup with a control system is developed to evaluate and showcase the implementation in real-world applications. Scheme 3 shows the best transition operation performance because the inverter maintains the same operating points (v, f, P, Q, and phase angle) during the transition operation, which guarantees that there are no/small transients during the MG transition operation. Therefore, we conclude that ensuring smooth MG transition operation requires the GFM inverter(s) to maintain the same operating points during the transition operation, which also minimizes the PCC power flow. Future work will be on testing Scheme 3 in a larger MG system with multiple GFM inverters.

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