Design of a Non-PLL Grid-Forming Inverter for Smooth Microgrid Transition Operation

Preprint

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National Renewable Energy Laboratory

Presented at the 2020 IEEE Power and Energy Society General Meeting (IEEE PES GM)
August 3–6, 2020

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-75332
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Suggested Citation
Wang, Jing, Blake Lundstrom, and Andrey Bernstein. 2020. *Design of a Non-PLL Grid-Forming Inverter for Smooth Microgrid Transition Operation: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-75332. https://www.nrel.gov/docs/fy20osti/75332.pdf.

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Design of a Non-PLL Grid-forming Inverter for Smooth Microgrid Transition Operation

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***Abstract*—This paper develops a controller for a grid-forming (GFM) inverter that is capable of operating as either a GFM or grid-feeding source that can improve the operation of a microgrid during on-off grid transitions through use of a novel synchronization approach. Furthermore, this controller avoids use of a phase-locked loop (PLL) and the inverter is able to synchronize with the grid with self-generated voltage and frequency. This prevents the inverter from replicating any grid voltage disturbances in its output—a key disadvantage of many grid-connected inverters that use a PLL. To enable fast synchronization, active synchronization control is adopted both during inverter start-up and microgrid reconnection operation and a method of coordinating synchronization of the inverter with a microgrid controller and grid interconnection circuit breaker is presented. Simulation results for multiple microgrid transition operations and unplanned islanding events demonstrate that the developed non-PLL grid-connected GFM inverter controller and synchronization method are effective in synchronizing the inverter and microgrid to the grid, avoiding phase jump during microgrid transition operation, and improving microgrid islanding transients versus a traditional configuration.**

***Index Terms*—Active synchronization control; grid-feeding; grid-forming; microgrid transition operation; non-PLL.**

I. INTRODUCTION

Today, increasing numbers of microgrids powered by distributed energy resources (DERs) are being installed worldwide. These installations are designed to operate both with or without a grid connection (i.e., grid-connected, islanded, and transitioning between grid-connected and islanded operation modes are all possible) to enhance power system resilience and reliability [1]. To smoothly transition between operation modes, a reliable grid forming (GFM) source is needed to maintain synchronism during the transition and establish a stiff bus voltage for the microgrid when in islanded mode [2]. This requires the GFM source to maintain its phase angle and keep the system state variables (voltage and current) continuous without instantaneous changes throughout the transition operation.

Synchronous generators are a natural candidate for a GFM source because the dynamics of generator's governor can maintain synchronism of the voltage phase angle and frequency and the generator's rotating inertia can damp disturbances during transition operation [3]. However, in many localities, current renewable energy portfolio standard legislation requires 100% renewable sources of electricity in the coming future (e.g., California's Senate Bill 100 [4] requires such in California by 2045). This means that more and more renewables will replace conventional generation. Therefore, using inverter-interfaced DERs as GFM sources becomes very important. However, inverter-interfaced DERs which do not have any rotating inertia, do not share the same dynamics/characteristics as synchronous generators; their dynamics are dominated by their programmed digital control [5]. Therefore, extensive efforts have been undertaken to improve the control strategies of GFM inverters and insert the desired dynamics to ensure smooth microgrid transition operation.

Existing control methods for GFM inverters can be categorized into two groups: (i) traditional voltage and current control methods, which must switch operation modes when transitioning between on-grid and off-grid operation, and (ii) synchronverter type control, which directly emulates the dynamics of a synchronous generator, without explicit voltage or current control loops. The traditional control strategy generally adopts active synchronization techniques, which adds the angle difference between the microgrid voltage and main grid voltage at PCC into the GFM inverter, to ensure synchronization is maintained when a microgrid reconnects to the main grid [6]; this is a topic still receiving much research attention. For synchronverter type control, integrated synchronization schemes, which adjust the internal voltage of the GFM inverter by mimicking the principles of a synchronous generator, have been developed [7]-[9]. However, the complexity and computation burden of these approaches can limit their applicability in real inverter controllers.

In [10], we previously developed a novel GFM inverter integrated synchronization control technique that uses traditional voltage control throughout both grid-connected and off-grid operation, obviating the need to transition between controllers, but prior to on-grid/off-grid transition, the angle difference in the GFM source must be properly compensated for. However, while this approach can achieve satisfactory performance during planned transitions, this approach still must switch between grid-connected and internal voltage references after ensuring synchronization and thus may not work well when unplanned islanding occurs; this is because it requires time to compensate for the angle difference. However, it is important to maintain the same phase angle in GFM inverter during microgrid islanding operation to avoid harmful transients. Furthermore, the control design in [10] and many other GFM inverter controller designs [2][6][11], leverages a phased-lock loop (PLL), which makes the GFM inverter susceptible to injecting harmful transients that may be present in the grid-side voltage into its output, reducing its benefit.

Therefore, this paper develops a GFM inverter controller that leverages the advantages of the traditional control (voltage

This work was supported by Alliance for Sustainable Energy, LLC, the manager and operator of the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding was provided by the U.S. DOE's Advanced Research Projects Agency-Energy (ARPA-E) NODES program. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

control) and synchronverter control (emulating synchronous machine without switching between angles) to ensure smooth synchronization under both planned and unplanned transitions. The developed approach also avoids the use of a PLL, ensuring better stability and dynamics during grid transient events.

II. Control Strategy of Non-PLL GFM Inverter

The control strategy of a GFM inverter in a microgrid is to ensure synchronization of voltage and keep the system state variables continuous without rapid changes during microgrid transition operation. To achieve these requirements, the following control strategies are adopted:

1) Use a self-generated frequency and phase angle for all operation modes. This avoids switching between a grid-following phase angle (grid-connected mode) and self-generated angle (islanded mode). To synchronize with the grid voltage during start-up, a synch check is implemented in the inverter controller to ensure that three-phase voltage magnitude, frequency, and phase angle between the inverter output voltage and grid voltage are within predefined thresholds before closing the circuit breaker of the GFM inverter. To allow the GFM inverter to connect with the grid quickly after start-up, an active synchronization control scheme is developed to make the inverter voltage (magnitude, frequency, and phase angle) approach that of the grid voltage and close the circuit breaker as soon as they are within predefined thresholds. Similarly, when the microgrid is going to reconnect to the main grid, an active synchronization control scheme can be designed in the GFM inverter to make the microgrid voltage at the PCC gradually approach the grid voltage at the PCC, thus ensuring that the microgrid smoothly reconnects to the main grid. Note that the GFM inverter keeps the same phase angle prior to and after microgrid islanding operation (planned and unplanned), and there is no need to do any angle compensation. This is different approach than [10].

2) Use the same control structure (voltage control) for both grid-connected and islanded (GFM) mode. This ensures that there are no discontinuities in the state variables throughout the transition operation. As explained in [11], voltage control can be implemented in grid-connected mode as well because of the duality between current and voltage. The injected current (power) can be indirectly controlled by controlling the inverter output voltage if an impedance exists between the grid and the inverter; because the inverter is usually connected with an output (e.g., LCL) filter, the impedance between the inverter and grid is often the impedance of this filter along with the impedance of the connective wiring. Thus, voltage control can be used to achieve power injection control in grid-connected mode.

III. Design of the Non-PLL GFM Inverter Synchronization Control

A. Control Schematic of the Non-PLL GFM Inverter

In this paper, we only study one GFM inverter connected in a microgrid, though we will study multiple GFM inverter configurations in future work. Based on the strategy determined in Section II, the control schematic of the non-PLL GFM inverter and the power system circuit, shown in Fig. 1, is developed. The circuit breaker at the inverter output is S_1 and the circuit breaker at the PCC is S_2. v_{DER}, v_{gDER}, v_{mg}, and v_g are the inverter terminal voltage, inverter grid-side voltage, microgrid voltage at the PCC, and the main grid voltage at the PCC, respectively. i_{abc}, v_{oabc}, and i_{oabc} are the measured inverter current, inverter voltage and inverter output current. The voltage control algorithm for the GFM inverter can be found in [11].

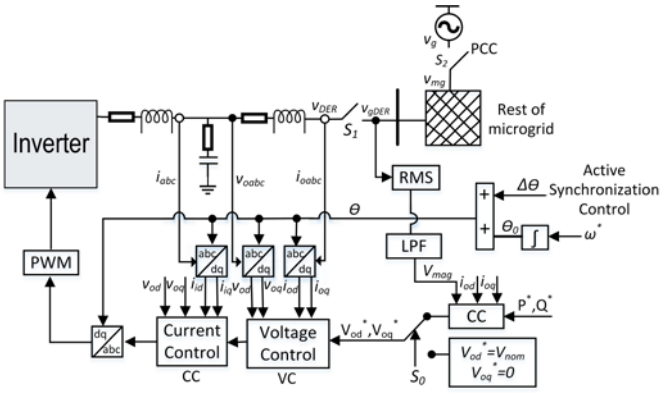


Fig. 1. Control schematic diagram of the grid-connected GFM inverter.

As shown in Fig. 1, the same phase angle, θ, is used for the Park transformation and inverse Park transformation, and there is no switch between angles when changing modes of operation. θ is the sum of the self-generated θ_0 and condition-generated $\Delta\theta$; here, $\Delta\theta$ is determined at inverter start-up, when the inverter is first connected to the grid-connected microgrid, via active synchronization control. Once synchronization is completed, $\Delta\theta$ is latched until the next time that the islanded microgrid is reconnected to the grid, at which time $\Delta\theta$ is modified based on active synchronization control with the grid voltage. In grid-connected mode, the voltage magnitude information of the grid side voltage (v_{gDER}) is needed to calculate the inverter's voltage reference. It can be calculated by using a PLL or root mean square (RMS) block (in this implementation an RMS calculation is used). S_0 is switched depending on the operation mode of the inverter and the microgrid status, as summarized in Table I.

Table I shows the three operation modes of the GFM inverter. Start-up and islanded modes share the same control scheme (voltage-frequency (VF) control with internal V^* and ω^* as the nominal references); however, the status of the circuit breakers S_1 and S_2 are opposite. The position of S_0 is determined as a logical AND of the status of circuit breakers S_1 and S_2. Note that if both S_1 and S_2 are "open," the microgrid voltage at PCC needs to be evaluated to check if the microgrid is live or not. If the microgrid is live, the GFM inverter performs start-up and synchronization similar to the case when the microgrid is grid-connected, and it continues VF control mode once connected to the islanded microgrid. Otherwise, the microgrid may be in blackout conditions and the inverter works in VF mode to black-start the microgrid system. The operation scenario of both S_1 and S_2 "open" will be studied in future work.

Table I. Operation Mode of GFM Inverter

Start-up	Grid-Connected	Islanded
VF control	PQ control	VF control
S_1 open S_2 closed	S_1 closed S_2 closed	S_1 closed S_2 open
S_0 "0"	S_0 "1"	S_0 "0"
Internal V^* and ω^* references as nominal value	P^* and Q^*, externally configured and set by microgrid controller	*Internal* V^* and ω^*, references as nominal value

B. Active Synchronization Control and Coordination Mechanism

The development of the synchronization control for start-up and reconnection is very similar. Both need to calculate the angle difference, $\Delta\theta$, with the target voltage and add it to the

original angle, θ_0, as shown in Fig. 1. In addition, coordination among the microgrid controller, PCC circuit breaker controller, and the GFM inverter is necessary to allow automatic operation for the transition operation scenarios. The overall design scheme of the synchronization control is presented in Fig. 2.

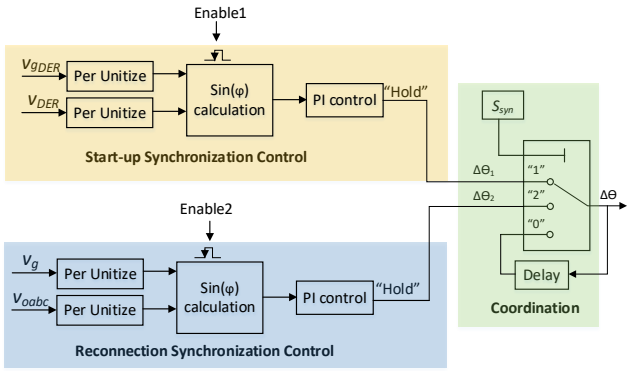


Fig. 2. Schematic diagram of the active syncrhonization control and coordination in the GFM inverter.

1) Coordination

The synchronization block coordinates the three elements (microgrid controller, PCC circuit breaker controller, and GFM inverter) to ensure smooth synchronization. It triggers the right synchronization block at the correct time to send out the compensated angle, $\Delta\theta$, and disables the block once the corresponding circuit breaker is closed. A signal named "S_{syn}" is used to output the correct compensation angle, $\Delta\theta$. Its value is defined based on the status of circuit breakers S_1 and S_2. If S_1 is "open" and S_2 is "closed" (start-up), S_{syn} is equal to 1. If S_1 is "closed" and S_2 is "open" (reconnection), S_{syn} is equal to 2. In all other situations, S_{syn} is equal to 0. As mentioned in Section II, the angle of the GFM inverter is maintained to be the same prior to and after the change of operation. This is achieved by holding the compensation angle after the change in operation, and this angle is used as the initial angle for the next operation mode.

2) Inverter Start-up Synchronization Control

During start-up, the GFM inverter works in VF mode and uses angle θ_0 for the Park transformation and control. After the voltage and frequency stabilizes to nominal values, the microgrid controller sets signal "Enable1" as "high" and sends it to the GFM inverter to initialize the start-up synchronization control block, which calculates the angle difference between the inverter voltage and the grid voltage. Inside this block, the target voltage (grid voltage) v_{gDER} and the controlled voltage (inverter voltage) v_{DER} are first per-unitized. Equation (1) and (2) are used to calculate $sin(\varphi)$ with $\varphi = \theta_{v_{gDER}} - \theta_{v_{DER}}$:

$$v_{gDER,a}v_{DER,a} + v_{gDER,b}v_{DER,b} + v_{gDER,c}v_{DER,c} = \frac{3}{2}cos(\varphi) = m \quad (1)$$

$$v_{gDER,a}v_{DER,b} + v_{gDER,b}v_{DER,c} + v_{gDER,c}v_{DER,a} = -\frac{3}{4}\cos(\varphi) - \frac{3\sqrt{3}}{4}\sin(\varphi) = n \quad (2)$$

Then, sin(φ) and cos(φ) can be calculated as:

$$\begin{cases} cos(\varphi) = \frac{2}{3}m \\ \sin(\varphi) = \frac{-2m-4n}{3\sqrt{3}} \end{cases} \quad (3)$$

When the angle difference, φ, is very small, $sin(\varphi) \approx \varphi$. φ is the angle error between the target voltage, v_{gDER}, and the controlled voltage, v_{DER}, and a proportional-integral (PI) controller is used to accumulate the error. The output of the PI controller is the input to the controlled plant (the GFM inverter) and adjusts the inverter's angle to reach the target. The proportional gain is 0.5 and the integral gain is 5.

At startup, S_1 is "open" and S_2 is "closed" and thus S_{syn} is equal to 1 and $\Delta\theta_1$ is selected as the output and added to θ_0. A synchronization check block is implemented in the circuit-breaker control of the inverter to close the circuit breaker only when the differences in voltage magnitude, phase angle, and frequency between the inverter voltage and the grid voltage are within the thresholds.

The inverter start-up synchronization check block is triggered by the "Enable1" signal so that it operates only during start-up synchronization. To ensure smooth and stable synchronization and account for initial conditions, a timer (e.g., ≥ 0.5 cycle) is used to guarantee that the angle difference is smaller than the threshold for at least this duration before enabling the circuit breaker. Once the circuit breaker S_1 is closed, the signal "Enable1" will be reset to "low." The synchronization check will then be disabled, and its output will be held "high" to keep the inverter's circuit breaker closed all of the time. At the same time, S_{syn} is equal to 0 after S_1 is closed and $\Delta\theta$ will become the initial value. Then the GFM inverter connects to the grid and works in grid-connected mode. Note that "Enable1" is determined based on the status of S_1 and S_2 and the request for connecting the inverter issued by the microgrid controller.

3) Microgrid Reconnection Synchronization Control

When the microgrid is going to reconnect to the main grid, the goal is to ensure that v_{mg} matches v_g. As the GFM source in the microgrid, the GFM inverter can adjust its output voltage to cause the microgrid voltage, v_{mg}, to eventually synchronize to the grid voltage, v_g. Like the start-up synchronization, if the differences in voltage magnitude, phase angle, and frequency between the microgrid voltage and the main grid voltage at the PCC are within the threshold, the PCC circuit breaker is then closed. Note that v_g and v_{mg} are not used directly as the inputs to the Reconnection Synchronization Control block because there is impedance between GFM inverter and the PCC circuit breaker and this causes a different angle difference between v_g and v_{mg}. Instead, v_g and v_{oabc} are used and grid voltage at the PCC (v_g) is a direction for inverter voltage (v_{oabc}) to follow rather than a specific set point.

If the microgrid is going to reconnect to the main grid, the microgrid controller will issue an enable signal "Enable2" to trigger the reconnection synchronization block. Because S_1 is "closed" and S_2 is "open," S_{syn} is equal to 2, and $\Delta\theta_2$ is selected as the output and added to θ_0. The inputs of the reconnection synchronization control block are the grid voltage at the PCC (v_g) and the inverter voltage (v_{oabc}). A synchronization check block similar to the one in the inverter circuit breaker controller is implemented in the PCC circuit breaker controller, and it is enabled by the signal "Enable2" to keep the operation coordinated. With the synchronization block running and tuning the angle difference, the microgrid voltage at the PCC will eventually get close to the grid voltage at the PCC. The differences will be within the threshold, and the PCC circuit breaker is then closed. Once the PCC circuit breaker S_2 is closed, the signal "Enable2" will be reset to "low." The synchronization check will then be disabled, and its output will be held "high" to allow the PCC circuit breaker to close. At the same time, S_{syn} is equal to 0 after S_2 is closed and $\Delta\theta$ will be held at the previous value.

IV. Simulation Results

In this section, numerical simulation is performed in MATLAB/Simulink to validate the performance of the proposed non-PLL GFM inverter controller and synchronization approach versus a traditional voltage/current control with PLL method (as

implemented in [10]). The microgrid model used for validation, which is detailed in [1], has two battery energy storage systems (BESSs) with inverters, two photovoltaic (PV) inverter units, and both residential and commercial buildings with load profiles. The first battery inverter system, BESS1 is the GFM source in the system and all other DERs (two PVs and BESS2) are grid-feeding sources to inject power to the grid. The load profile updates every 1 s. During the simulation scenario, the microgrid controller requires the GFM inverter to connect to the grid at t = 1 s, the microgrid system has a first unplanned islanding from the main grid at t = 6 s. The microgrid is requested to reconnect to the grid at t = 15 s and finally a second unplanned islanding event occurs at t = 25 s. The two unplanned islanding events occur at different grid voltage conditions, with the purpose of demonstrating the robustness of the developed GFM inverter control approach to multiple possible grid voltage conditions.

Fig. 3 shows the key measurements of the microgrid during this scenario with the traditional method ("With PLL") and the newly developed approach ("non-PLL"), including the PCC circuit breaker status (top row of plots), the microgrid PCC RMS voltage in per unit (middle), and frequency (bottom). It can be seen that during microgrid islanding (t=6 s and 25 s) and reconnection (t=15 s) the new approach has slightly better transient performance in measured PCC voltage and much better transient performance in frequency. This is because there is no phase jump when using the non-PLL method, while there are phase jumps using the PLL-based method during microgrid transition operation. This affects the frequency significantly.

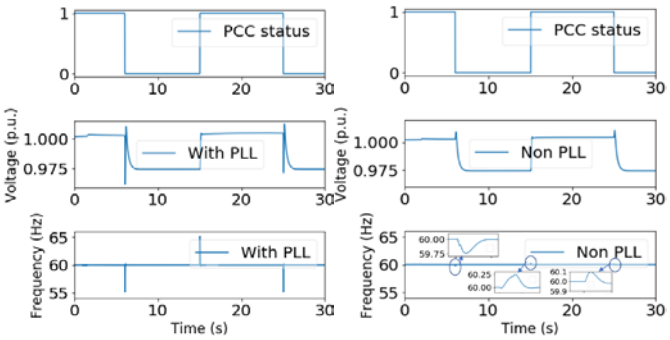


Fig. 3. Results of the full microgrid simulation scenario: PCC circuit breaker status, PCC voltage RMS, and frequency.

The GFM battery starts up at t = 0 s and stabilizes to nominal voltage and frequency in a few cycles. It is requested to connect to the grid at t = 1 s from the request signal "Enable1." The start-up synchronization control is enabled to compute the compensation angle $\Delta\theta_l$. This compensation angle quickly decreases as the phase angle difference between the battery voltage, v_{DER}, and grid voltage, v_{gDER}. As shown in Fig. 4, the angle difference is reduced quickly to a very small value, and the circuit breaker is closed around t = 1.9 s. Once the circuit breaker is closed, the signal "Enable1" is reset to "low" and the compensation angle $\Delta\theta_l$ is latched to maintain the same angle in grid-connected mode. The zoomed-in figures of battery voltage and grid voltage during the time the inverter is requested to connect to the grid (t = 1 s) and the time the inverter connects to the grid (t = 1.9 s) are presented to portray the process and effectiveness of the active synchronization control during the start-up synchronization process. The results verify that the start-up synchronization works as expected to connect the inverter smoothly to the grid without creating transients in the grid voltage.

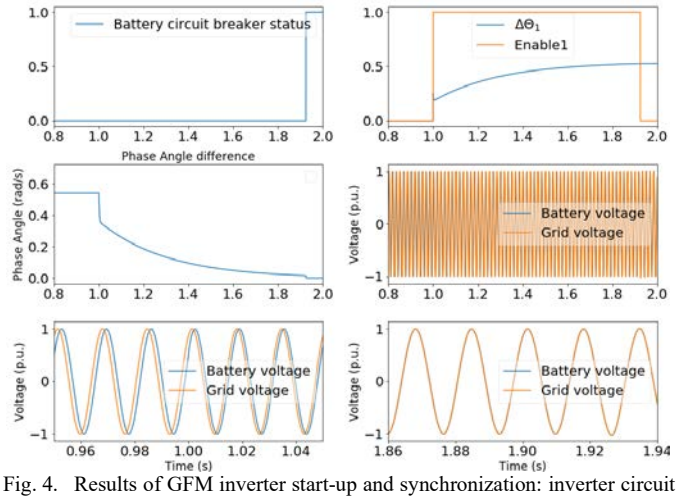
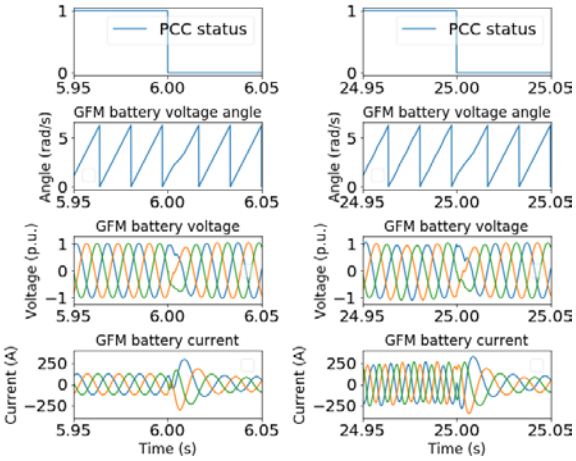
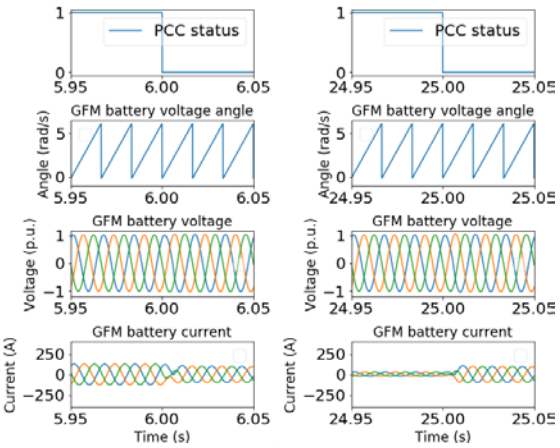


Fig. 4. Results of GFM inverter start-up and synchronization: inverter circuit breaker status, synchronization control to enable the signal and compensation angle (top right), angle difference between inverter voltage and grid voltage, and battery voltage and grid voltage.

Test results of microgrid unplanned islanding (t=6 s and 25 s) with the traditional PLL-based method and the proposed method are shown in Fig. 5 (a) and Fig. 5 (b) respectively. As seen from Fig. 5 (a), a phase jump is observed in the phase angle of the GFM inverter at both disconnection time points with traditional method. Because the GFM inverter switches from the phase angle following the grid voltage to the self-generated phase angle after microgrid is disconnected. Thus, the output voltage waveforms of the GFM inverter exhibit abrupt changes in phase angle, which causes significant transients during the disconnection process. This is also shown in the GFM inverter current on the bottom of the Fig. 5 (a). Since it is unplanned islanding, there is no way to compensate the angle difference after PCC circuit breaker is already open. These results show the drawback of using the traditional method which switches between grid-following angle and self-generated angle. Fig. 5 (b) shows the key measurements when the microgrid disconnects from the main grid using the proposed method. During microgrid islanding operations, the angles of the GFM battery inverter show continuity without a phase jump or interruption because of using the same phase angle. The GFM battery output voltage and current shows very smooth waveforms without transients during microgrid islanding operation. The current swaps the phase at t=6 s because the battery is commanded to charge before disconnection and switch to discharge after disconnection. The results indicate that keeping the same phase angle for the GFM inverter without need for compensation, as in the proposed method, is important to ensuring smooth transients during unplanned islanding.



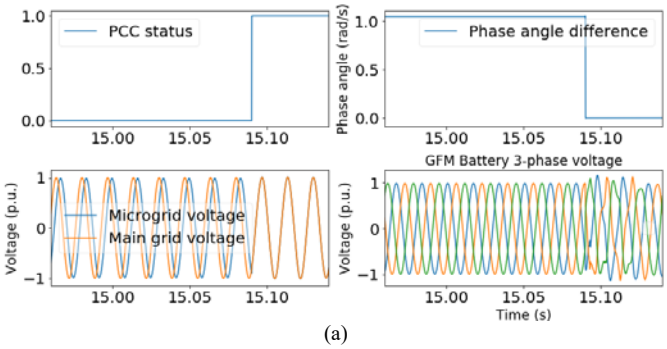
(a)



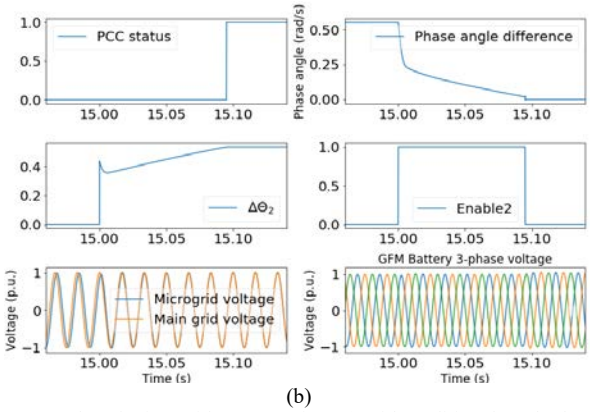
(b)

Fig. 5. Results of microgrid unplanned islanding operations (a) with traditional method and (b) with proposed method: PCC circuit breaker status, voltage angle of the GFM battery, GFM battery voltage, and microgrid voltage at the PCC.

Test results of microgrid reconnection (t=15.09 s) with the traditional PLL-based method are shown in Fig. 6 (a). Since there is no phase angle synchronization control in the GFM inverter, a phase angle difference between microgrid voltage and main grid voltage at PCC exists during reconnection. This directly causes phase jump in the microgrid voltage at PCC and the GFM inverter. Thus, the output voltage waveforms of the GFM inverter exhibit abrupt transients during microgrid reconnection. The results of the microgrid reconnection operation using the proposed method are shown in Fig. 6 (b). The microgrid is requested to reconnect to the main grid at t = 15 s, and the reconnection synchronization control is enabled at the same time. The computed compensation angle, $\Delta\theta_2$, makes the angle difference between the microgrid voltage and the main grid voltage at the PCC smaller and smaller and allows for use of a smaller angle sync check threshold. The circuit breaker at the PCC is closed near t =15.09 s when voltage magnitude, phase angle, and frequency are within the thresholds. The voltage waveforms of the microgrid and the main grid at the PCC during the reconnection show that the microgrid voltage approaches the main grid voltage and finally overlaps. When the microgrid reconnects to the main grid, the microgrid voltage, the main grid voltage at the PCC, and the GFM battery voltage all show very smooth waveforms, with negligible transients observed. The results shown in Fig. 6 indicate that the designed resynchronization control algorithm is effective to synchronize the microgrid voltage to the main grid voltage and to enable a smooth reconnection transition.



(a)



(b)

Fig. 6. Results of microgrid reconnection (a) with traditional method and (b) with proposed method: PCC circuit breaker status, angle difference between microgrid voltage and main grid voltage at the PCC, compenstion angle, resynchronization control enabling signal, microgrid voltage and grid voltage at the PCC, and GFM battery voltage.

V. CONCLUSIONS

This paper presents a synchronization scheme of a non-PLL grid-connected inverter that works as GFM source in all microgrid operation modes to achieve seamless microgrid transition operation. This synchronization scheme includes inverter start-up, microgrid disconnection, and reconnection operation. The developed synchronization scheme is validated in MATLAB/Simulink model of a sample microgrid with a GFM battery inverter source. The simulation results show that the developed non-PLL GFM inverter works effectively to synchronize the inverter to the grid and synchronize the phase angle of the GFM source during microgrid transition operation especially under unplanned islanding to achieve smooth transients. In future research, we will study multiple GFM inverter scenarios and further demonstrate how the designed non-PLL GFM inverter control improves stability in microgrid grid-connected mode by avoiding a PLL.

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