Time-Disciplined Non-PLL Active Synchronization for Grid-Forming Inverters

Preprint

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National Renewable Energy Laboratory

Presented at the 2021 IEEE Texas Power and Energy Conference (TPEC)
February 2–5, 2021

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-77579
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Suggested Citation
Meyers, Toby, and Barry Mather. 2021. *Time-Disciplined Non-PLL Active Synchronization for Grid-Forming Inverters: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-77579. https://www.nrel.gov/docs/fy21osti/77579.pdf.

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Contract No. DE-AC36-08GO28308

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February 2021

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This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work was supported by the Laboratory Directed Research and Development (LDRD) Program at NREL. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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Time Disciplined Non-PLL Active Synchronization for Grid Forming Inverters

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***Abstract*—Two major issues facing grid-forming inverters are synchronism and phase reference inaccuracies. Prior literature has addressed these problems with solutions such as disciplining the phase reference using GPS and active synchronization modes but these methods have not yet been integrated together. This paper serves to unite solutions and develop a means for an inverter to remain synchronized and grid-forming without phase reference inaccuracies through a novel time-disciplined active synchronization phase reference. Further, this work expands upon prior literature on active synchronization to include black-start capabilities. Finally, the time disciplined phase reference is evaluated in Simulink as a grid-forming inverter capable of any synchronization circumstance and assessed by key metrics from modern standards.**

***Index Terms*—grid forming inverter, GPS, time discipline, non-PLL, droop, synchronization, blackstart**

I. INTRODUCTION

The grid, and many microgrids by extension, could experience frequency-related issues from lack of inertia due to grid-following inverters (GFLIs) [1]. Already in California, several large-scale faults have turned into blackouts from the poor fault ride through of GFLIs [2]–[4]. Through using their own voltage and frequency setpoints, grid-forming inverters (GFMIs) resist changes from the grid in a phenomenon known as inertia which is further improved by removing phase-lock loop (PLL) dependency [5]. Unlike GFLIs, GFMIs must align with the grid while still relying on their own internal reference in a condition known as synchronization.

For microgrid applications, traditional inverter synchronization involves switching between GFMI and GFLI controls for grid connection but this transition can lead to undesirable phase hops that could trip the dedicated GFLIs offline [6]. The desired control method is one by which the inverter can constantly remain in GFMI mode with a means for maintaining synchronization as demonstrated in [7]. However, the controller from [7] did not consider blackstart synchronization (as demonstrated for GFMIs in [8]) nor clock-based inaccuracies.

Clock inaccuracies present another major challenge to isochronous GFMIs whose phase reference is generated internally, typically from the controller's crystal. Depending on the complexity and cost of the crystal, the error will gradually accumulate over time but is typically compensated by droop. As droop compensates for crystal inaccuracies over time, the theoretical inertia is reduced since the converter becomes more dependent on the grid through droop rather than its internal reference. One solution to this problem is disciplining the microcontroller's internal phase reference using the highly accurate time-bases found on GPS (Global Positioning System) satellites as described in [9]. The time discipline method considered in this paper involves a one pulse per second (PPS) square wave from the GPS time-base (or receiver) that resets a counter from the internal crystal circuit providing a highly-accurate phase reference. With minimal dependence on droop, the GPS-disciplined droop-based GFMI method can be considered to provide infinite-inertia since the system has no dependence on the grid neither through PLL nor droop.

Assuming a low bandwidth communication means for coordination, this paper builds upon prior literature to integrate GPS time discipline with four categories of synchronization: (1) Initial Grid Synchronization, (2) Ride Through, (3) Black-start Coordination, and (4) Grid Reconnection Coordination as shown in Fig. 1. The content is presented as follows: first, the active synchronization phase reference will be presented and discussed. Then, relevant inverter standards will be addressed and key metrics extracted. Finally, a droop-based GFMI will be simulated in Simulink with means to operate in each synchronization mode.

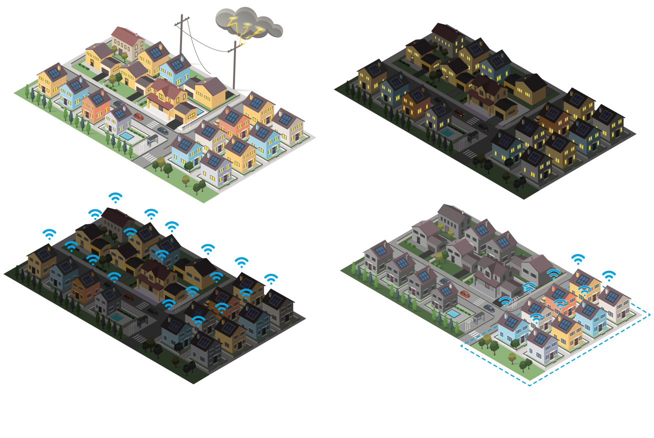

Fig. 1. Categories of Synchronization.

II. SYNCHRONIZATION CATEGORIES

Similarly to [7], the main objective of categorizing synchronization events is to minimize disturbances and maximize stability. In addition, it is desirable to minimize communications to and from inverters which will improve resilience but completely removing communications is not always practical for grid-connected inverters. From the four categories in Fig. 1, two require communications for coordination with external parties when grid-connected. This coordination is critical for either safety (blackstart) or system planning purposes (microgrid reconnection) since microgrids typically island for financial reasons or during an emergency outage.

A. Ride Through

The first synchronization category is ride through which maintains frequency and phase with the grid during normal operations. Its main objective is to remain connected with the grid during one of many common circumstances: planned/unplanned islanding, load/generation disturbances, faults, recloser events. These common events are tied together since none of them require inverter-inverter communications given a GFMI with enough inertia to ride through the disturbance as is the case with time disciplined active synchronization. Hence, the key metric here is inertia for true isochronous operation measured as frequency variance.

To generalize time disciplined active synchronization, dq-based GFMI control is divided into modules shown in Fig. 2. As this work's main contribution is specific to the phase generator module, existing literature methods will be implemented to produce a voltage reference [10] and regulate the voltage source inverter in dq frame [11] for the final simulation. As a starting point, the phase generator of Fig. 3, similar to [9], provides a solid phase reference (Fig. 4) but has no means for non-PLL synchronization.

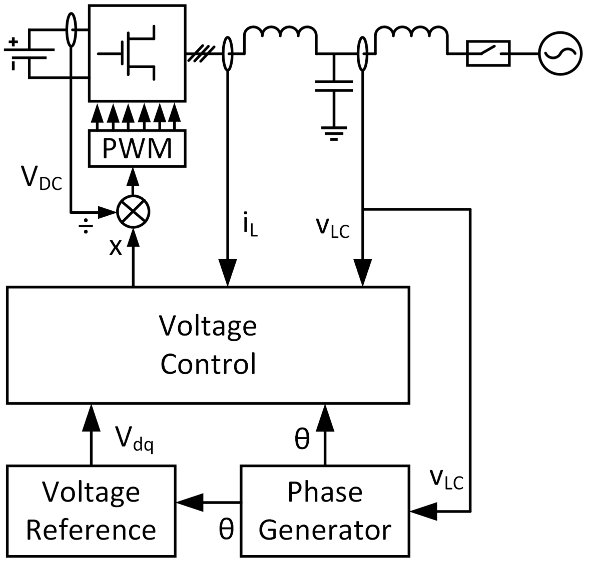

Fig. 2. DQ-based Grid Forming Control Modules.

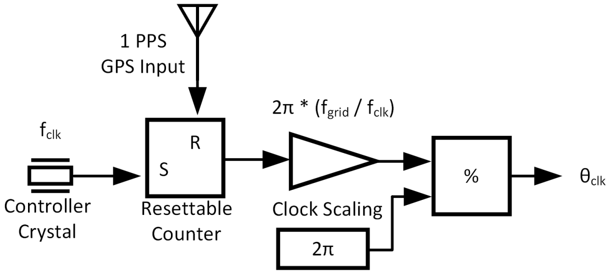

Fig. 3. Time Disciplined Phase Generator.

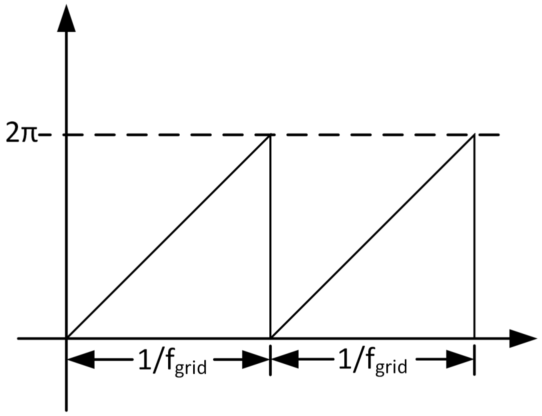

Fig. 4. Ideal Phase Generator Output Waveform.

B. Initial Grid Synchronization

The next synchronization category is Initial Grid Synchronization, responsible for initial phase reference calibration to the existing stiff grid before the converter enables its output. Its main objective is minimizing voltage and frequency disturbances to the grid upon connection. Unlike GFLIs which can simply ramp up their power output to avoid disturbances, GFMIs need to synchronize both with the grid and their load setpoints before steady-state can be reached due to droop or other internal mechanisms. This paper's implementation involves calibrating the internal phase reference to the grid's phase with a PLL to detect grid phase zero-crossings and reset the internal clock at that point as shown in Fig. 5.

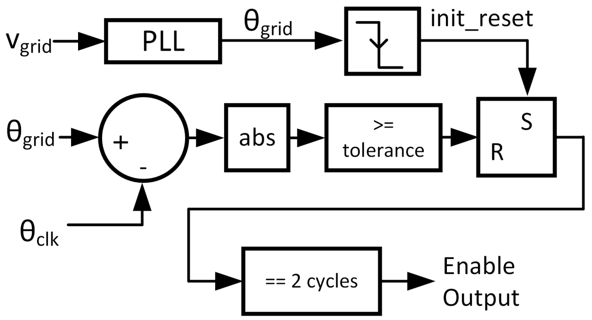

Fig. 5. Initial Grid Synchronization.

C. Blackstart Coordination

Moving on to communication-based synchronization modes, Blackstart Coordination restarts the grid quickly while providing cold load pickup. The blackstart coordination mode is critical for inverter-dominated grids and restarts the grid quicker than traditional means. It is implemented by simply restarting the phase and outputting at a communicated and planned time. This method was demonstrated for GFMIs using VOC in [8] and can be extended to time disciplined active synchronization. Blackstart coordination, as defined here, could also fit in with blackstart schemes as in [12] which suggests starting DER by category (i.e. wind, battery, solar) through disseminating different starting times based on the inverter's generation source. Today, NERC EOP-005-3 only requires a written plan from system operators for traditional top-down power plant blackstart [13] but can be extended to utilize the increasing amounts of DER using this mode.

D. Grid Reconnection Coordination

Grid Reconnection Coordination has the focus of reducing phase hop on reconnection from an islanded system. Without any reconnection mechanism, droop could handle the phase difference but the frequency variance might trip other generation sources or loads offline. In this mode, unlike Initial Grid Synchronization, the output is enabled so phase changes must be gradual enough to prevent significant frequency changes while also being quick enough to prevent droop, a phasor quantity, from compensating. Another method from [11] is directly feeding through the PLL input to the phase reference during reconnection which would significantly reduce inertia, possibly leading to undesirable frequency variance. In this paper's implementation (Fig. 6), a PLL is used once again to obtain a phase difference between the grid and internal reference. This difference is added to the internal reference, but not directly fed through, until the inverter and grid are aligned, at which point, the PCC (Point of Common Coupling) is closed. Per IEEE 1547.4 [14] and discussed in [7], this method would be considered as active synchronization since the inverter slowly and deliberately changes its phase angle reference to match the grid.

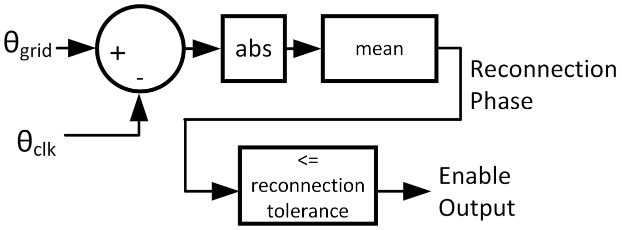

Fig. 6. Grid Reconnection Coordination.

III. METRICS

Generators and inverters alike have existing standards that are used to regulate and evaluate control systems. For instance, NERC PRC-024-2 [15] requires generation owners properly set their optional protective settings but this is further specified for distributed energy resources (DER) in IEEE 1547. IEEE 1547 specifically discusses functionalities and settings required of grid-connected inverters for connection to a stiff grid [16]. The limits given depend on several factors but the most relative and stringent requirements are summarized in Table I.

IEEE 1547.4, the supplemental guide to IEEE 1547 for DER islands, divides inverter island functionality into modes [14] but for GFMIs, these can be simplified as in Table II. With a time disciplined phase generator, the fully isochronous GFMI provides enough inertia (as shown in [9]) such that [7]'s category of microgrid disconnection can be considered simple ride through. Additionally, IEEE 1547.4 specifies that islanding inverters have two primary objectives: (1) providing sufficient voltage and frequency regulation under mode change or while islanded, (2) inverters must be IEEE 1547 compliant while grid-connected. Finally, IEEE 1547.4 requires that islanded inverters must have enough DER capacity to blackstart their islanded system. With these standards summarized, the metrics given in Table I must be met for GFMIs mode, however while islanded, the metrics will be dependent on the island's stability properties and protection settings. Since this paper's focus is frequency reference and synchronization, special consideration will be given to frequency-related metrics including frequency limits, rate of change of frequency (ROCOF), enter service frequency, and reconnection tolerance frequency/phase in the simulation. Issues related to overvoltage and voltage step can be solved by modification of the droop and voltage loop but are out of scope for this paper.

IV. SOFTWARE IMPLEMENTATION

For the time disciplined non-PLL GFMI control system, the mechanisms discussed replace the simple phase generator of Fig. 3 with the active synchronization enabled phase generator in Fig. 7. This phase generator is modeled in Simulink using the generic GFMI from Fig. 2 and tested through connection to a simple microgrid. The simplified microgrid consists of a local load rated to 1.5 kW and 300 VAR with a 60 Hz swing bus voltage source connected on the PCC's grid-side as in the case of a facility microgrid. To test out all four modes, inputs summarized in Table III were provided to the Simulink model for direct validation of the initialization, ride through, and reconnection modes. In another test, the blackstart mode was validated using the local load with no grid connection.

V. RESULTS AND DISCUSSION

For the first testing case consisting of inputs from Table III including initialization, ride through, and reconnection, measurements were taken at the inverter's output and at the PCC's grid-side. In the second testing case of a local microgrid blackstart, measurements were only taken at the inverter's output since the PCC remained open throughout blackstart testing. The data presented in this section for both testing cases consists of instantaneous three-phase voltage waveforms, frequency, and the rate of change of frequency (ROCOF)

TABLE I
IEEE 1547 RELEVANT METRICS

Requirement	Limit	Section of IEEE 1547-2018
Absolute Voltage	0.7 - 1.1 PU	6.4
Absolute Frequency	58.5 - 61.2 Hz	6.5
ROCOF (Ride Through)	0.5 Hz/sec	6.5.2.5
Enter Service	0.917 - 1.05 PU Voltage 59.5 - 60.1 Hz	4.10.2
Reconnection Tolerances (with respect to the Grid)	0.1 Hz Frequency (59.9 - 60.1 Hz) 3% PU Voltage 10° phase	4.10.4
Initial Grid Synchronization	Maximum EPS Line Voltage 138% for <1 cycle	7.4

TABLE II
IEEE 1547.4 MODE COMPARISON

Framework Mode	IEEE 1547.4-2011 Mode	Section of IEEE 1547.4-2011
Reconnection Coordination	Reconnection Mode	4.4.4
Ride Through	Area EPS-connected Mode (normal parallel operation)	4.4.4
	Transition-to-Island Mode	4.4.2
	Island Mode	4.4.3

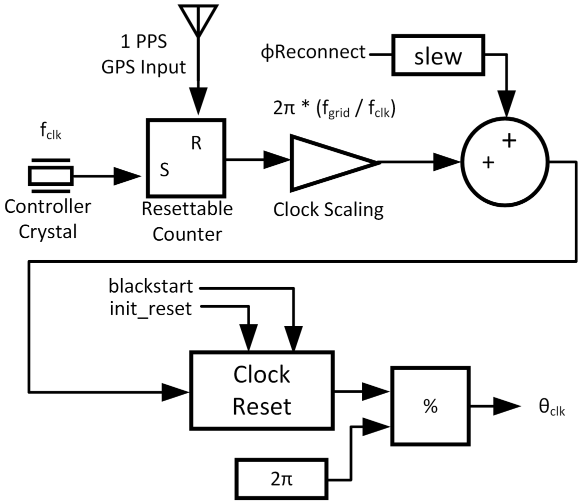

Fig. 7. Combined Synchronization Control.

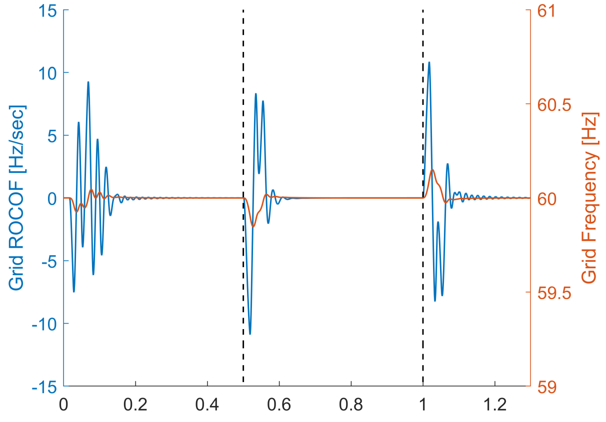

Fig. 8. Grid ROCOF (in Blue) and Frequency Variance (in Red) Waveforms with Table III Mode Change Intervals (in Black).

TABLE III
SIMULINK TEST PROCEDURE

Input Mode	Time
Initialize	1 ms
Open PCC (Islanding Ride Through)	0.5 sec
Reconnect	1 sec

which are shown in Fig. 8 - 13 and summarized in Table IV. From Table IV it can be seen that all frequency measurements are within the absolute frequency limits presented in Table I but two frequency measurements, taken at the inverter's output, are slightly above the IEEE 1547 specific limits. During initialization, the inverter (Fig. 9) shows a brief fluctuation of frequency at 60.18 Hz, 0.08 Hz above the enter service limit of 60.1 Hz and, during reconnection the inverter measurement shows 60.38 Hz, 0.28 Hz above the reconnection limit. The inverter in these cases went over the category's frequency but never exceeded the absolute frequency limits because load-generation balancing was the assumed priority given a sole inverter. Further, the overfrequencies occurred after connection with the grid during stabilization. From the grid's perspective (Fig. 8), these frequency changes are smoothed out by the load and parasitic inductances. In the case of a blackstart (Fig. 12), the frequency remains within all necessary limits for the local load. Regarding ROCOF, all of the measured ROCOFs momentarily exceeded the ROCOF limit in part due to the extremely low inertia of the load and swing bus voltage sources. In a direct application, the microgrid modeled is closer to a facility microgrid with a sole generation source than a community microgrid with multiple inverters which would further reduce frequency variation.

TABLE IV
SIMULATION RESULTS SUMMARY

Category/Measurement	**Min Frequency [Hz]**	**Max Frequency [Hz]**	**Min ROCOF [Hz/sec]**	**Max ROCOF [Hz/sec]**
Initialization (Inverter)	59.79	60.18	-12.81	11.13
Initialization (Grid)	59.92	60.05	-7.523	9.278
Ride Through (Inverter)	59.56	60.01	-12.51	13.04
Ride Through (Grid)	59.85	60.02	-10.89	8.336
Reconnection (Inverter)	59.94	60.38	-13.02	12.52
Reconnection (Grid)	59.97	60.15	-8.252	10.85
Blackstart (Inverter)	59.83	60.08	-9.996	7.26

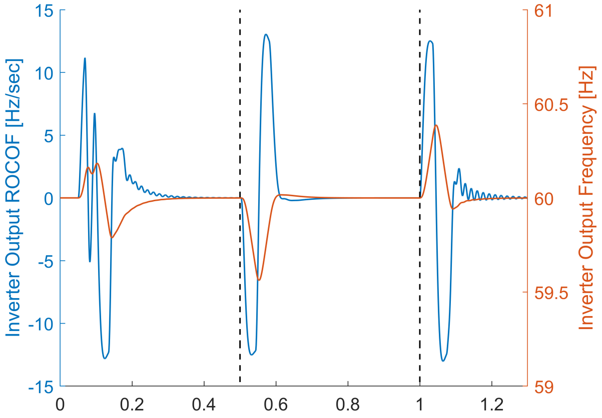

Fig. 9. Inverter ROCOF (in Blue) and Frequency Variance (in Red) Waveforms with Table III Mode Change Intervals (in Black).

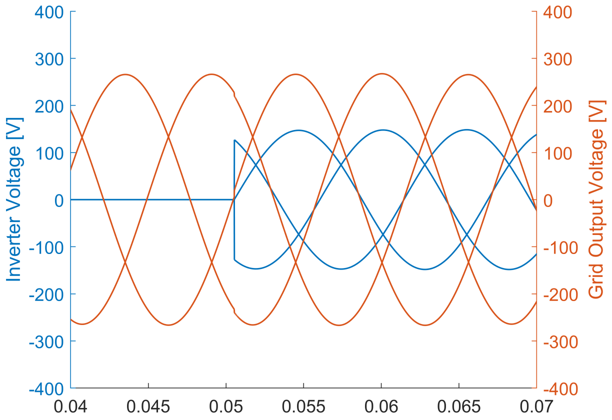

Fig. 10. Inverter Output Voltage (in Blue) and Grid Voltage (in Red) During Initialization Event per Table III.

For the initialization mode, the voltages seen in Fig. 10 show the inverter begins outputting once the internal phase reference has been successfully synchronized with the grid, hence, the inverter output waveform is perfectly in phase with the existing grid upon startup. In this instance, the initialization signal was sent at 1 ms and the inverter began outputting at 50 ms. In Fig. 11, the grid voltage drops upon reconnection due to power sharing of the grid and local inverter through droop.

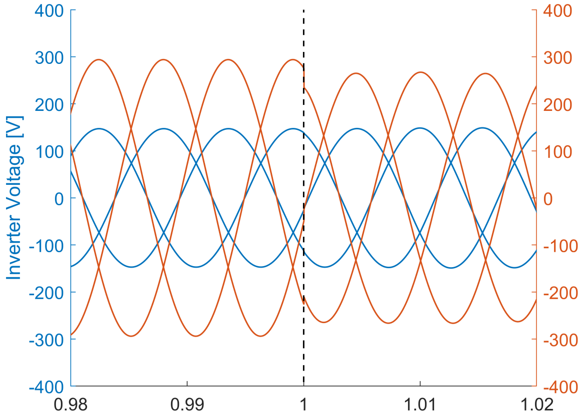

Fig. 11. Inverter Output Voltage (in Blue) and Grid Voltage (in Red) During Reconnection Event per Table III.

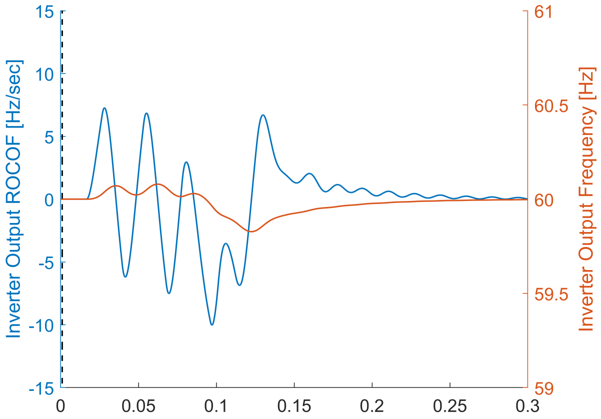

Fig. 12. Inverter ROCOF (in Blue) and Frequency Variance (in Red) Waveforms with Blackstart Mode Change Interval (in Black) at 1 ms.

Finally, in Fig. 13, once the inverter receives a blackstart flag at 1 ms, it immediately begins outputting at nominal voltage and frequency while assuming zero initial phase. This differs from the initialization case where the flag was received at 1 ms but the inverter had to synchronize its internal reference with the power system and did not begin outputting until 50 ms.

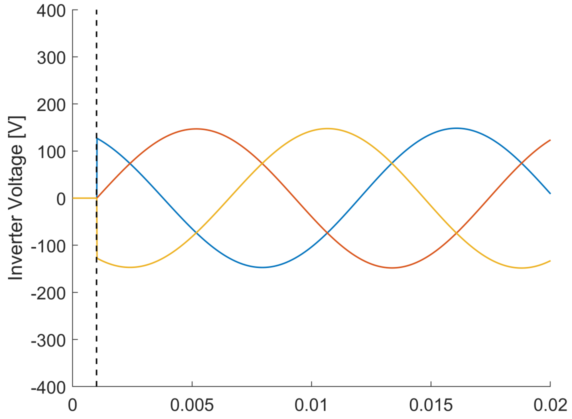

Fig. 13. Inverter Output Voltage During Blackstart Event with Mode Change Interval (in Black) at 1 ms.

VI. Conclusion

Issues associated with the traditional mode switch from GFMI to GFLI can be resolved by developing a synchronization method and remaining in GFMI. Further, stability concerns regarding internal phase reference can be resolved through using a time disciplined phase reference with no direct feedthrough from PLL. In this paper, these solutions are combined to develop an active synchronization phase generator for GFMIs with a means to assess them according to existing standards such as IEEE 1547, IEEE 1547.4, NERC EOP-005-3, and NERC PRC-024-2. The simple microgrid modeled in this paper consisted of a swing bus and local load so the system was fairly sensitive and weak as in the case of a facility microgrid. The next steps of this work include scaling the control method presented and implementing in hardware at a large scale.

VII. Acknowledgements and Disclaimer

This work was authored by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work was supported by the Laboratory Directed Research and Development (LDRD) Program at NREL. 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.

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