Investigating Multi-Microgrid Black Start Methods Using Grid-Forming Inverters

Preprint

Elliott Fix,[1] Abhishek Banerjee,[1] Ulrich Muenz,[1] and Gab-Su Seo[2]

1 Siemens
2 National Renewable Energy Laboratory

Presented at the 2023 IEEE Conference on Innovative Smart Grid Technologies North America (ISGT NA)
Washington, D.C.
January 16–19, 2023

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Conference Paper
NREL/CP-5D00-83956
January 2023

Contract No. DE-AC36-08GO28308

Investigating Multi-Microgrid Black Start Methods Using Grid-Forming Inverters

Preprint

Elliott Fix,[1] Abhishek Banerjee,[1] Ulrich Muenz,[1] and Gab-Su Seo[2]

1 Siemens
2 National Renewable Energy Laboratory

Suggested Citation
Fix, Elliott, Abhishek Banerjee, Ulrich Muenz and Gab-Su Seo. 2023. *Investigating Multi-Microgrid Black Start Methods Using Grid-Forming Inverters: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-83956. https://www.nrel.gov/docs/fy23osti/83956.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-83956
January 2023

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

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. Funding provided by U. S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Investigating Multi-Microgrid Black Start Methods Using Grid-Forming Inverters

Elliott Fix, Abhishek Banerjee, Ulrich Muenz
Autonomous Systems and Control, Siemens
Princeton, New Jersey, USA
{elliott.fix, abhishek.banerjee, ulrich.muenz}@siemens.com

Gab-Su Seo
PSEC, National Renewable Energy Laboratory
Golden, Colorado, USA
gabsu.seo@nrel.gov

***Abstract*—This paper examines state-of-the-art microgrid (MG) black-start technologies with grid-forming (GFM) inverter-based resources (IBRs) and proposes black start and interconnection methods for 100% inverter-based MGs. A multiple-MG approach is proposed and compared to the existing methods in a 4-bus, 12-GFM inverter simulation test setup. This investigation involves intelligent synchronization units that enable the autonomous synchronization of multiple MGs based on their terminal measurements. MGs in this setup are held at different loading levels and comprise averaged models of GFM inverters. The results of the black-start techniques are compared, and conclusions are drawn to better prepare MG planners and distribution system operators for next-generation, multi-MG, GFM inverter-based, black-start procedures.**

***Index Terms*—black start, inverter-based resources, microgrid, bottom-up restoration, grid-forming inverter, synchrobreaker.**

I. Introduction

More frequent natural disasters due to climate change and threats of cyber-physical attacks cause power systems to be more vulnerable to outages [1]. Considerable progress has been made in the decarbonization of the energy sector with the increase of renewable energy penetration via inverter-based resources (IBRs) [2]. Distributing IBRs across the power system also increases its resilience to cyber-physical attacks. To recover from outages, microgrid black start methods have garnered attention [3], [4]. As renewable IBRs replace fossil fuels, they must support the robust control and reliability functions provided by traditional generation, from voltage/frequency control to black-start recovery procedures [4].

A black start is a power system contingency plan that reenergizes a grid after a blackout. Black starting MGs is a critical topic for future power systems to fully incorporate IBR technology. Inverter-based MGs have more generation units in a smaller footprint, shorter interconnections, and a proportionally more-diverse assortment of inverter technologies than bulk power systems; the MG black-start process is for these reasons quite complex [5]. The *Research Roadmap on Grid-Forming Inverters* published by the National Renewable Energy Laboratory in 2020 specifically urges a technological thrust to design grid-forming inverters that are capable of black-starting power systems [6]. The majority of IBR technology developed has been centered on IBR controls for normal operation, e.g., voltage and frequency control, and fault supports, such as fault ride-through [7]. Contrarily, black-start capabilities of GFM IBRs have drawn less attention with limited scope; further development is critical for wide field deployment for use in both bulk power systems and MGs [1]. Various publications have proposed MG black-start methods dependent on a grid connection and mix of thermal generation and IBRs [8], [9] as well as IBRs alone [3], [10], [11]. Reference [11] coordinates a black start between two inverters with the help of a centralized controller. In [12], MGs are used as black-start resources to support the the bulk power system. Additionally, [13] achieves the synchronization of an islanded MG and a bulk grid via communication between the IBRs.

Based on the literature review, there is limited work on 100% GFM inverter-based MG black-start research. This study proposes alternative black-start methods for 100% inverter-based MGs and their subsequent synchronization. Our investigation stands apart from prior efforts by proposing new black-start methods that prioritize various metrics, e.g., critical load recovery time or frequency stabilization with more GFM assets. The motivation for multi-MG system black starts is in remote, isolated locations or those that have lost their bulk power system connection. Second, the proposed black-start methods require minimal communication. The minimal control necessary for our black start is a single on/off enable signal to each inverter. Third, the proposed methods rely on 100% inverter-based resources and not current industry-common diesel-based black start units.

Funded by U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office under DE-EE0008769. 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.

II. Multi-Microgrid black-start Strategies

MGs inherently have lower system inertia than bulk grids and they are more sensitive to switching events, e.g., connecting or disconnecting breakers that interface MGs to the grid (or other MGs) as well as connecting or disconnecting individual generation and load units. Consequently, MGs are also more likely than bulk power systems to be downed by unexpected events such as the sudden loss of a generation or load unit or short circuit. These events, in addition to MG protection schemes, blackout detection, soft starts, unbalanced loading, faults, and over/under voltage and frequency events are outside of the scope of this paper.

One key component of our multi-MG black start is the synchrobreaker (SB) that enables the synchronization and then physical connection of MGs. To determine if two MG buses

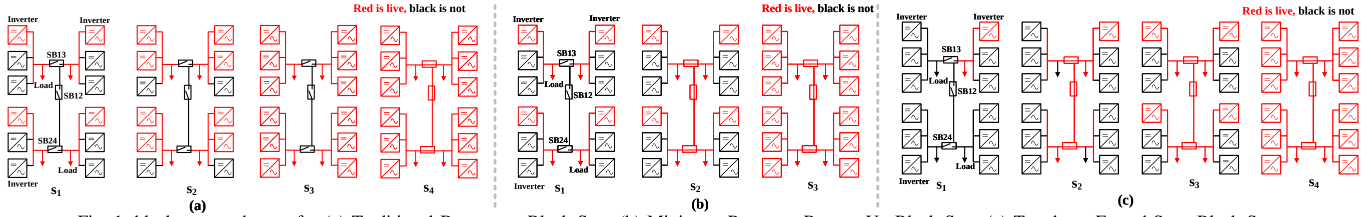

Fig. 1: black-start pathways for (a) Traditional Bottom-up Black Start (b) Minimum-Resource Bottom-Up Black Start (c) Top-down Forced-Sync Black Start.

can be connected physically, the SB reads the local voltage waveform on both buses that it is connected to. Five metrics must be met before the breaker closes: phase A, B, and C voltage differences must be within the voltage difference threshold, the phase angle difference measured via phase-lock-loop (PLL) on each of the two buses must be within the phase difference threshold, and the SB must be given an enable signal. When these conditions are met, the breaker closes and the MGs are coupled. A synchronization method is also required to minimize the disturbances of a weak, low-inertia MG when connecting additional energy sources, e.g., GFM inverters. The approach we designed to synchronize multiple GFM inverters is similar to [11].

As per current literature, no standard thresholds exist for the interconnection of MGs or the connection of individual GFM IBRs to islanded MGs during black starts. In section 4.10 of IEEE Std. 1547-2018 [14], standards are established for an inverter to enter service, including frequency, voltage, and phase differences for synchronous interconnection. The difference in frequency between two MGs can be described:

$$\Delta f_{ij} = m_d \left(\frac{p_i}{n_i} - \frac{p_j}{n_j} \right) \tag{1}$$

where Δf_{ij} is frequency deviation between MG i and j, m_d is inverter frequency droop gain, p_i and p_j are baseline loading, and n_i and n_j are generation capacity factor with same y-axis intercept assumed. With this in mind, one should minimize the impact of switching events when interfacing multiple MGs as well as prioritizing the connection of critical loads during contingencies. This investigation develops two black start methods that address these opportunities for improvement.

A. Method 1: Traditional Bottom-Up Black Start

For the bottom-up implementation in simulation, we follow an existing process similar to [10]. To perform our standard multi-MG bottom-up black start, each MG is individually powered up by its own black-start unit. Similar to bulk power system black starts, MGs shed their load to a minimum for the black start. Also, inverter soft-start, i.e., voltage ramp up, to mitigate inrush currents of motors and transformers is assumed. Other inverters then synchronize and connect. The black-start process for Method 1 is shown in Fig. 1(a): In stage (a)s_1, the anchor inverter in each MG black starts to energize its own load bus with SBs open. Next, in stage (a)s_2, the second inverters synchronize and connect to individual MGs to share power via droop with the anchor inverters. In (a)s_3, the third inverters follow the same process as the second inverters. The MGs are now fully energized but not synchronized with each other. In the final stage, (a)s_4, the SBs close at their next opportunity and connect the MGs.

B. Method 2: Minimum-Resource Bottom-Up Black Start

In contrast to Method 1, a method that reduces the impact of switching events and microgrid synchronization is proposed. In this method, only one inverter in each isolated MG is enabled when the MGs are synchronized and connected. After connection, other inverters may turn on at random to fully energize the system. The proposed minimum-resource black-start method is depicted in Fig. 1(b): with SBs open, in (b)s_1, the anchor inverter in each MG black starts to energize its own load and bus. In (b)s_2, the SBs are permitted to connect MGs; no other inverters turn on until the MGs are synchronized. In the final stage (b)s_3, the rest of the inverters connect.

The core concept in this energization plan is to connect the MGs as soon as possible. This retains the same load shedding requirement with Method 1. Our hypothesis is that if fewer inverters were connected to each minimum-MG, the transience when interconnecting MGs would be less than when compared to fully-energized MGs. For our simulation, we enabled the inverters in a logical order for easier data analysis than random enable signals.

C. Method 3: Top-down Forced-Sync Black Start

The last method proposed is akin to top-down black starts in bulk power systems. Method 3 establishes only one inverter in the system as the anchor black-start unit. It first energizes its own MG. Then, the SBs close one by one so that the anchor inverter establishes a voltage to all buses.

This black-start method is shown in Fig. 1(c): Method 3 starts with stage (c)s_1 where one anchor inverter black-starts to energize its own load and bus voltage. In (c)s_2, The SBs are forced to close and voltage is now available for all inverters to synchronize to. Only critical loads in other MGs should be energized at this point to avoid overloading. In stage (c)s_3, remaining inverters connect and load breakers are closed one by one leading to the full recovery. In the final stage (c)s_4, the remaining inverters are enabled and connect when synchronized with the grid.

The motivation for this black-start method is to swiftly recover critical loads that do not have black-start-capable GFM assets or are in distant MGs. This method can be used to improve resilience with worst-case-scenario power system failures in mind; Methods 1 and 2 do not permit the closure of a breaker until the voltage phasor differences are within the thresholds on both buses. In the event that a local MG has lost all of its generation capacity in Method 1 or 2, the SB will not close. The top-down forced-sync black-start method is the only potential avenue to energize critical MG loads with no local generation. As a result, Method 3 would require the anchor inverter to be rated at higher power than ones using Method 1 and 2, to sustain potentially higher baseline/minimum loads as well as inrush currents from other MGs. To achieve a successful black start, firstly, the baseline loads must not exceed the power rating of the single anchor inverter. Second, the power flow from one MG to another must not exceed the line limits. Third, care must be taken when forcing a breaker to close and energizing a downed line due to arcing and possible faults on the blacked-out MG. These and similar issues remain outside of the scope of this investigation.

III. Multi-Microgrid Test System

The simulation test system comprises four MGs interfaced by SBs. The single line diagram of the MG setup is depicted in Fig. 2, where each MG has one true anchor GFM inverter capable of black start (Inverter X.1). As it can be seen in Fig. 2, there exist line impedances between the buses connecting the inverters, and the value of the line impedance is chosen such that R>X. The MGs all operate at different load levels; reactive power loading is neglected in the scope of this study. The parameters used in the simulation are detailed in Table I.

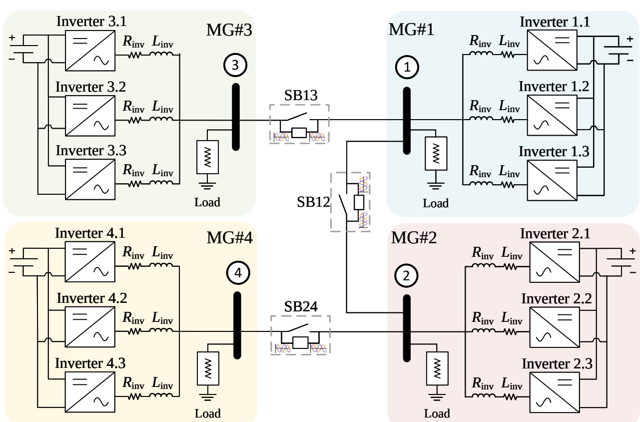

Fig. 2: Single line diagram of the 4-microgrid, 12-inverter simulation testbed.

An averaged model of GFM inverters is used, and each inverter has the same LCL filter at its output stage. Figure 3 depicts the overall inverter structure with control diagram and the breaker logic. The inverters operate in droop control with inner current and outer voltage control loops.

If one were to implement SBs at medium- to high-voltage bulk power systems, it is recommended that they have stricter sync criteria to avoid catastrophic transients. This is evident in the IEEE 1547's synchronization parameter limits in Table II; this standard enforces stricter threshold requirements for higher kVA rated interconnections of aggregated IBRs [14].

IV. Results and Discussions

A. MG Forced Closure and Inverter Synchronization

We begin our discussion by validating the need for MG syncronization methods. As shown in Fig. 4, the traditional

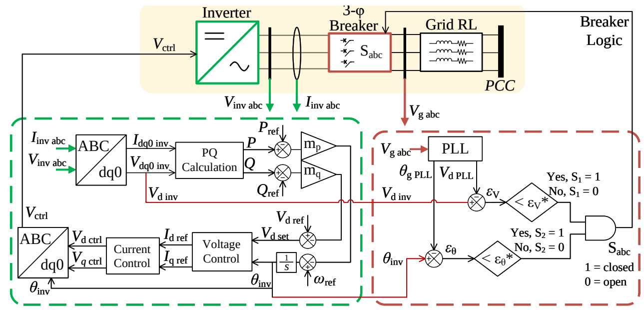

Fig. 3: Grid-forming inverter control diagram.

TABLE I: Microgrid Simulation, Parameters

Parameter	Value	Units
Simulation Time Step	20	μs
Nominal RMS Voltage, line-to-line	480	V
Nominal Frequency	60	Hz
Real Power Load, MG1	1.6	kW
Real Power Load, MG2	2.0	kW
Real Power Load, MG3	1.8	kW
Real Power Load, MG4	2.2	kW
Reactive Power Load, MGs 1,2,3,4	0	VAR
Inverter Droop Gain m_P	0.03	-
Inverter Droop Gain m_Q	0.15	-
All Inverter Filter L	1.125	mH
All Inverter Filter C	11.5	μF
Line Impedance	0.9703	Ω
Line X/R Ratio	0.0848	-
Inverter Voltage (V_d) Difference Threshold	5	V
Inverter Phase (θ) Difference Threshold	0.01	rad
SB Voltage Difference Threshold for A,B,C	10	V
SB Phase (θ) Difference Threshold	0.2	rad

bottom-up black start is performed but the SBs are forced to connect at 10, 12, and 14 s. This results in undesired real power spikes; our syncrobreaker reduces this transience.

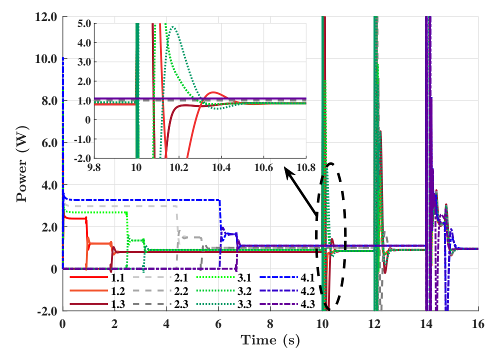

Fig. 4: Real power during black start when breakers are forced to close; notice how drastic the spikes are when connecting MG to MG without waiting for the synchronization logic.

Before further discussion of the three methods is conducted, our individual inverter 'enter service' procedure must be clarified. Each inverter operates at 61 Hz until it is connected as seen in the frequency plots of Fig. 5 (a), (b), and (c). This is done purposely to reduce the time it takes for each inverter to connect during the black start. When the inverter is synchronized with the grid and its breaker closes, the internal frequency reference is then switched from 61 to 60 Hz and droop control is enabled. Because frequency and instantaneous phase are intrinsically coupled, the only way to modify the difference in instantaneous phase between two signals is to increase their frequency mismatch. In IEEE 1547, an inverter shall not enter service when the grid operates below 59.5 Hz or above 60.1 Hz [14], which we ignore for black-start purposes. By adding a constant deviation to the measured grid frequency reference, an inverter will be guaranteed to drift in and out of

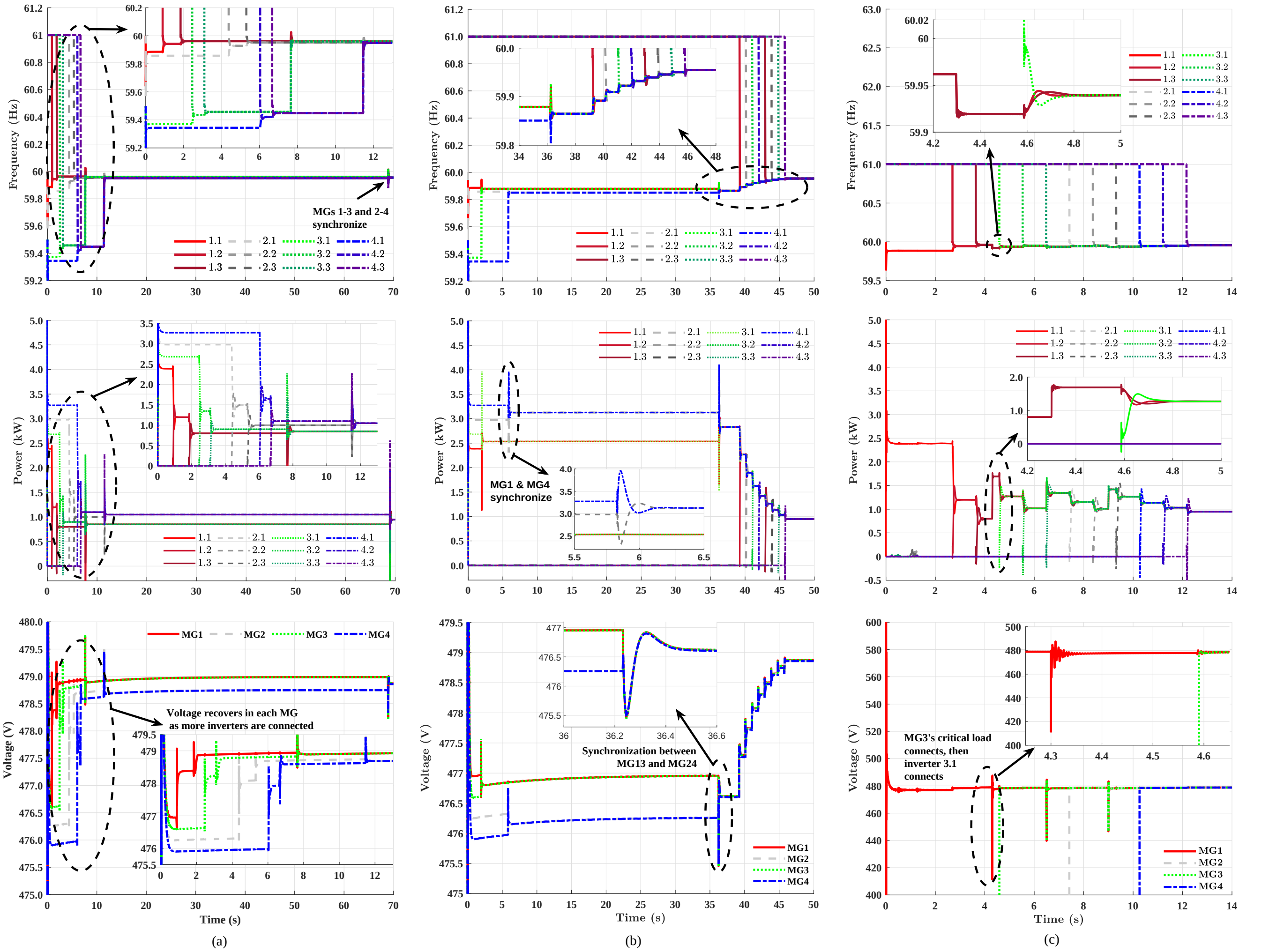

Fig. 5: Simulation results showing row-wise frequency, real power, and V_d: (a) traditional (Method 1), (b) minimum-resource bottom-up (Method 2), and (c) top-down forced-sync.

phase with the grid. We used a 1 Hz deviation to accelerate our simulation, but as little as a 0.1 Hz deviation may be sufficient in a real microgrid black start.

TABLE II: Comparison of IEEE 1547 [14] and Sync Threshold Values in This Study.

	Rating of DER units (kVA)	Frequency diff. (Δf, Hz)	Voltage diff. (ΔV, $\%$)	Phase angle diff. ($\Delta \phi^{\circ}$)
IEEE 1547 Thresholds	0 - 500	0.3	10	20
	500 - 1500	0.2	5	15
	>1500	0.1	3	10
SB Thresholds	<100	0.5	4.8	11.46
Inverter Thresholds	-	-	1.04	0.57

The simulation results of all three black-start methods are shown in Fig. 5. It should be reemphasized that the inverter and SB threshold settings and the power levels of the MGs are the same in all three simulations, shown in Tables II and I. The exact timing of the inverter connections can be found in Table III. The 'Enable' column shows when a binary on/off signal is given to the inverter to begin synchronization; 'Connect' is when the inverter physically connects to the grid.

B. Simulation 1: Bottom-Up black-start Results

In Simulation 1, the MGs are energized independently, and the inverters are enabled one at a time on the MGs in ascending power level. As shown in Fig. 5, column (a), the frequency and voltage of each MG recover as the inverters come online and share more power. The initial anchor inverter that turns on in each MG is stable. MG1 is energized first, then MG3, then MG2, then MG4. There is minimum transience upon connecting the second and third inverters in each MG. When all of the inverters are injecting power to their respective local MGs, the SB synchronization is enabled.

A salient result of this simulation is that it took ≈ 54 s for the combination of MGs 1 and 3 to sync with the combination of MGs 2 and 4. This time delay is caused by the difference in phase seen at both sides of the SB. Because the frequencies of the two MG combinations are so close, the phase difference changes very slowly as explained in Section IV.A. Only when the phase difference is below the threshold does the final SB close and the whole system is connected near 68 s. The frequencies of the MGs are not exactly the same due to the relationship stated in eq. (1). Note that there is no secondary control to correct frequency deviations; the SB operates passively between two MGs. Another important metric that can be observed from Simulation 1 is the transience in frequency, power, and voltage during the MG interconnection events (when the SBs close, also shown in Table III).

C. Simulation 2: Minimum-Resource Bottom-Up Black Start

Similarly to Simulation 1, Fig. 5 Column (b) contains plots at scale to Column (a). This method prioritizes the early synchronization of multiple MGs and also has the added benefit of less transience during switching events than Simulation 1. Simulation 2 completes the MG synchronization and energization in 47 s. In contrast, Simulation 1 required 68 seconds. This difference is due to the frequency difference between the combination of MGs 1 and 3 and the combination of MGs 2 and 4. With regards to the metric mentioned in the previous subsection, Simulation 2 presents visibly reduced transience in frequency, power, and voltage upon MG interconnection when compared to Simulation 1.

D. Simulation 3: Top-down Forced-Sync Black Start

Simulation 3 is inherently different from Methods 1 and 2; the SBs do not synchronize passively. They are forced to connect when a single anchor inverter provides a voltage reference. In our simulation, the SB13, SB24, and SB12 close at 0.5, 1.0, and 1.25 s accordingly. Once the MGs are connected, the inverters are enabled one by one and are free to synchronize and connect. This method eliminates nearly all of the transience upon the connection of SBs by forcing them to close when only one inverter in MG1 is injecting power.

The simulation was conducted to perform three load increases. First we simulate the energization of a critical load in MG3 when only MG1 is powering the whole system as highlighted in Fig. 5 (c). Next, the inverters in MG3 turn on, but the load in MG2 is connected in tandem with inverter 3.3 to see how drastic the transience during the combination of a load change and inverter connection would be. A final load step occurs at 9 s when MG4's load breaker closes. This simulation supports our claim that we can energize critical load in physically distant MGs by force-closing SBs in a top-down black-start fashion. The inverters in that MG can then synchronize based on the bus voltage and we avoid a SB closure that may create undesired frequency spike/sag or real power flow in a particularly weak, low-inertia MG.

TABLE III: Inverter Enable and Breaker-closure Connection Times in Each Method.

		Simulation 1		Simulation 2		Simulation 3	
MG	**Inverter**	Enable (s)	Connect (s)	Enable (s)	Connect (s)	Enable (s)	Connect (s)
1	**1**	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.50	0.89	39.22	39.22	2.00	2.69
	3	1.25	1.84	42.91	42.91	2.75	3.63
2	**1**	0.00	0.00	0.00	0.00	6.50	7.42
	2	4.00	4.37	38.5	40.13	7.50	8.37
	3	4.50	5.31	42.5	43.85	8.50	9.32
3	**1**	0.00	0.00	0.00	0.00	4.00	4.59
	2	2.00	2.45	39.50	41.05	4.75	5.53
	3	2.75	3.09	43.50	44.80	5.75	6.48
4	**1**	0.00	0.00	0.00	0.00	9.50	10.26
	2	5.60	6.04	41.50	41.97	10.50	11.21
	3	6.20	6.67	48.50	45.75	11.50	12.16
SB13		7.00	7.65	1.00	1.94	*	0.50
SB24		9.00	11.47	4.00	5.83	*	1.00
SB12		11.00	68.92	7.00	36.23	*	1.25

V. Conclusion and Future Directions

This paper analyzes three different black-start methods for a GFM-dominated multiple microgrid setup and provides detailed analysis of each method, highlighting their associated merits and de-merits. Metrics like total time from blackout to complete restoration, number of switching operations, maximum change in voltage/frequency during the black-start sequences have been outlined in a 4-bus, 4-MG, 12-inverter simulation setup. Another technological advancement from this paper is the design and implementation of SBs which enable the reduced transient connection of multiple MGs. Moreover, the thresholds pertaining to the SBs have tighter limits as compared to existing IBR interconnection standards, making them particularly robust and conservative in nature. This publication's main focus is to propose black-start strategies but not to compare strategies in depth to claim that one method is preferred over another. The three methods outlined in this paper have their own merits and should continue to be considered in future MG black start, synchronization, and interconnection research.

Further investigation is necessary to perform a detailed examination of the simulation data to draw empirical differences between the methods. Additionally, hardware testing is essential to push this paper's efforts towards deployment. Future improvements will also include removing the system's dependence on phase-lock-loop reference generation and improving the system's autonomy.

References

[1] B.-M. S. Hodge, H. Jain, C. Brancucci, G.-S. Seo, M. Korpås, J. Kiviluoma, H. Holttinen, J. C. Smith, A. Orths, A. Estanqueiro *et al.*, "Addressing technical challenges in 100% variable inverter-based renewable energy power systems," *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 9, no. 5, p. e376, 2020.

[2] P. Denholm, P. Brown, and W. Cole, "Examining supply-side options to achieve 100% clean electricity by 2035," National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2022.

[3] H. Jain, G.-S. Seo, E. Lockhart, V. Gevorgian, and B. Kroposki, "Blackstart of power grids with inverter-based resources," in *Proc. IEEE Power & Energy Society General Meetings*, 2020, pp. 1–5.

[4] A. Banerjee, A. Pandey, U. R. Pailla, G.-S. Seo, S. Shekhar, H. Jain, Y. Lin, X. Wu, J. Bamberger, and U. Muenz, "Autonomous microgrid restoration using grid-forming inverters and smart circuit breakers," in *IEEE Power & Energy Society General Meeting*, 2022, pp. 1–5.

[5] S. Li, Q. Yu, H. Zhang, S. Gao, Y. Song, D. Wang, and J. Tang, "A hierarchical multi-agent evaluation scheme for integrating distributed energy resources in distribution systems," in *International Conference on Renewable Power Generation (RPG 2015)*, 2015, pp. 1–6.

[6] Y. Lin, J. H. Eto, B. B. Johnson, J. D. Flicker, R. H. Lasseter, H. N. Villegas Pico, G.-S. Seo, B. J. Pierre, and A. Ellis, "Research roadmap on grid-forming inverters," National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2020.

[7] S. Xu, Y. Xue, and L. Chang, "Review of power system support functions for inverter-based distributed energy resources- standards, control algorithms, and trends," *IEEE Open J. Power Electron.*, vol. 2, pp. 88–105, 2021.

[8] D. Chakravorty, D. Gutschow, X. Zhang, N. Miller, and D. Auty, "System restoration strategies using distributed energy resources," in *CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution*, vol. 2021, 2021, pp. 1445–1449.

[9] I. Beil, A. Allen, A. Tokombayev, and M. Hack, "Considerations when using utility-scale battery storage to black start a gas turbine generator," in *IEEE Power & Energy Society General Meeting*, 2017, pp. 1–5.

[10] Y. Du, H. Tu, X. Lu, J. Wang, and S. Lukic, "Black-start and service restoration in resilient distribution systems with dynamic microgrids," *IEEE J. Emerg. Sel. Topics Power Electron.*, pp. 1–1, 2021.

[11] F. Sadeque, D. Sharma, and B. Mirafzal, "Multiple grid-forming inverters in black-start: The challenges," in *IEEE Workshop on Control and Modelling of Power Electronics (COMPEL)*, 2021, pp. 1–6.

[12] Y. Zhao, Z. Lin, Y. Ding, Y. Liu, L. Sun, and Y. Yan, "A model predictive control based generator start-up optimization strategy for restoration with microgrids as black-start resources," *IEEE Trans. Power Sys.*, vol. 33, no. 6, pp. 7189–7203, 2018.

[13] Y. Du, H. Tu, and S. Lukic, "Distributed control strategy to achieve synchronized operation of an islanded mg," *IEEE Transactions on Smart Grid*, vol. 10, no. 4, pp. 4487–4496, 2019.

[14] "IEEE guide for using ieee std 1547 for interconnection of energy storage distributed energy resources with electric power systems," *IEEE Std 1547.9-2022*, pp. 1–87, 2022.