Black Start of Unbalanced Microgrids Harmonizing Single- and Three-Phase Grid-Forming Inverters

Preprint

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Black Start of Unbalanced Microgrids Harmonizing Single- and Three-Phase Grid-Forming Inverters

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***Abstract*—As power systems are transforming with increasing penetrations of inverter-based resources (IBRs), system restoration using IBRs has drawn attention. Using distributed grid-forming (GFM) assets located near critical loads, either three-phase or single-phase, to establish microgrid voltages in the absence of a bulk grid, a distribution system could obtain high system survivability. For swift and secure recovery of a critical load in a single-phase lateral, local single-phase GFM inverters can form a microgrid, and then it can be combined with a neighbouring grid with the inverters remaining in GFM mode for voltage and frequency regulation until the bulk grid comes online. It leads to dynamic interoperation of single-phase GFM inverters with three-phase ones in the black start process. This paper studies the novel approach with electromagnetic transient (EMT) simulations. To evaluate the potential and the technical challenges of the heterogeneous IBR-driven black start, three-phase and single-phase GFM inverter models are developed, including negative-sequence control for voltage balance and a phase-by-phase current limiter (three-phase) and current magnitude limiter (single-phase). To examine dynamic aspects of the black-start process, the EMT simulation also models transformer and motor dynamics emulating their inrush and startup behavior as well as network dynamics. Involvement of grid-following assets to facilitate the black-start process is also modeled. By allowing multiple GFM inverters to collectively black start without leader-follower coordination, regardless of phases, a system can achieve extreme resilience. An inverter-driven black start of a heavily unbalanced 2-MVA distribution feeder using 1 three-phase and 3 single-phase GFM inverters is demonstrated. The simulation shows the heterogeneous system can maintain stability with the single-phase GFM dynamics coupled with the three-phase one.**

***Index Terms*—Inverter-driven black start, grid-forming inverter, inverter-based resource, negative-sequence control, single-phase grid-forming, system restoration.**

I. Introduction

Increasing penetrations of inverter-based resources (IBRs) in modern power systems, such as photovoltaic, wind turbines, and battery energy storage, have drawn attention to understanding the potential of using these nonsynchronous resources to provide black-start support, i.e., as kick-starters for a large thermal power plant or black-start resources [1]–[4]. A black-start resource is a generator that can start to establish a grid, without needing external voltage formed. Black-start capability has been exclusively provided by synchronous generators [5]. To establish grid voltage using a power electronics inverter without a preformed voltage, grid-forming (GFM) inverters are required [6]. Energy storage devices can be designed with GFM and black-start capability for the inverter-driven black start [7]. Using their short startup time and fast dynamic performance of IBRs, a power system can black start and restore critical loads, unlocking the path to extreme grid resilience using local GFM assets [2], [8].

The concept of black-starting a power system with GFM inverters poses technical challenges and opportunities stemming from the fundamental differences of power electronics inverters from synchronous machines. First, the inverter's limited short-circuit current (in general, 1.1 p.u.–1.5 p.u. vs. 6 p.u.–8 p.u. of synchronous machines) should be given careful attention for a successful black start because it involves startup currents exceeding device-rated values, making IBRs operate close to their limits [9]. On the other hand, in some cases, inverters can address some issues using their soft-start capability [10], [11]. In addition, parallel inverter operation without leader-follower coordination should be considered to match the baseline loads. Inverters are sized at smaller scales than synchronous machines; therefore, it is likely that collective black start with multiple IBRs would be needed to restore a sizable system. Involving multiple inverters in a decentralized manner would be beneficial for system resilience; systems can recover with a fraction of the system damaged or offline by not relying on a dedicated asset [7]. To secure grid resilience in a remote service area susceptible to grid events, local single-phase GFM inverters could form a microgrid, and they can combine with and collectively maintain a three-phase grid, which is under-explored in literature. For a distribution system black start, voltage imbalance resulting from unbalanced loading should be addressed. A voltage balancing control like one reported in [12] can be used. Since this method uses an isochronous mode of operation, however, it is not straightforward for a black-start using parallel GFM operation.

This paper contributes to addressing these aforementioned challenges and developing solutions for resilient black starts using GFM IBRs. The key contribution is to investigate the heterogeneous black-start concept, involving both three-phase and single-phase GFM inverters in a decentralized manner to achieve a resilient black start. The multiple GFM inverter-driven black start has been proposed in [2] and demonstrated in [7], [13], but the heterogeneous configuration causing the dynamic interaction of three- and single-phase GFM inverters in the black-start process has not been studied. To evaluate the

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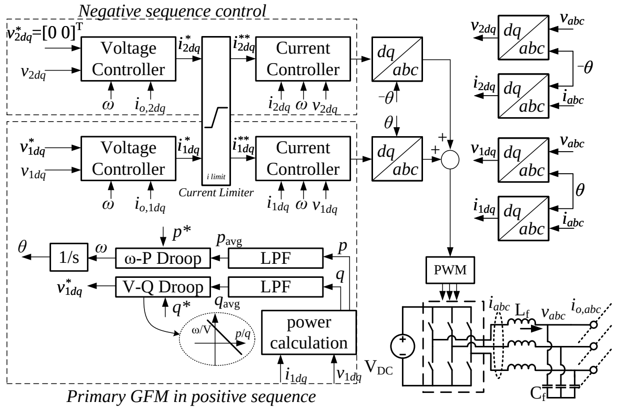


Fig. 1: GFM inverter control diagram including negative-sequence voltage compensation.

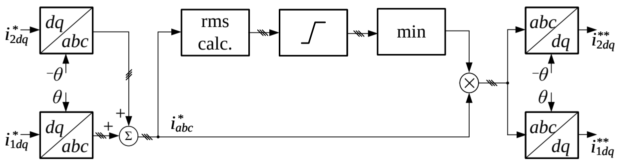


Fig. 2: Phase-current limiter for positive- and negative-sequence current controller.

potential of the concept, this paper develops detailed electromagnetic transient (EMT) simulations. The GFM inverter in the simulation includes a phase-by-phase current limiter and voltage balancing control for unbalanced loading (three-phase GFM) integrated with the droop primary control, and current magnitude limiter (single-phase GFM). Grid-following (GFL) IBR operation during black start is also included in this study. In a 2-MVA distribution simulation system with transformers and motors modeled to capture their inrush currents, it is demonstrated that a successful black start can be achieved with collective operation of one three-phase GFM and three single-phase IBRs—each emulating aggregated dynamics of multiple smaller scaled assets, maintaining voltage balance and sharing unbalanced system loading without leader-follower coordination through a stabilizing dynamic mechanism.

II. EMT Models for GFM Black-Start Study

This section provides modeling details of GFM and GFL inverters, transformers, and loads.

A. GFM Inverter Models

1) Three-Phase Droop-Controlled GFM Inverter with Negative-Sequence Control: The control architecture of the droop GFM inverter is illustrated in Fig. 1. For use in distribution system and black start, it employs a negative-sequence control integrated with a classical droop control for phase voltage balancing with voltage and current loops. Since distribution feeders are usually unbalanced and imbalance in instantaneous loading may be aggravated due to the sequential recovery nature of black start, potentially causing power quality issues, a measure to balance phase voltages should be used in an inverter-driven distribution system black start. In this study, a negative-sequence control to mitigate the feeder voltage imbalance is used, reported in [12]. The negative-sequence control, as shown in Fig. 1, runs in parallel with

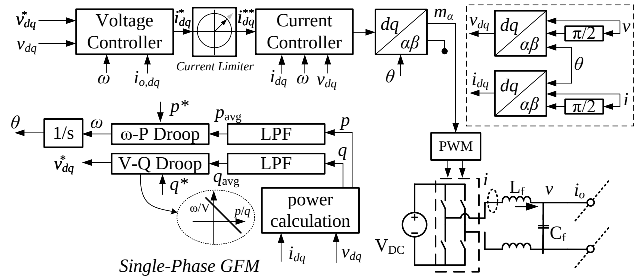


Fig. 3: Single-phase GFM inverter in dq reference frame with a current magnitude limiter.

the primary control and modulates the final control command to improve the voltage quality. Band-stop filters are used to filter the double-line frequency (120-Hz) components in the dq transformation.

For unbalanced overloading and fault scenarios, conventional current-limiting method, limiting three-phase average current, could result in suboptimal performance, potentially leading to an inverter exceeding the thermal limit of power switches. To limit phase currents, the control architecture shown in Fig. 2 is used integrating the solution in [12]. It monitors the rms current of each phase, and if it detects an overcurrent in a phase, it scales down the references based on the most severe phase current to retain the current angle.

2) Single-Phase Droop GFM Inverter: The diagram of the single-phase GFM inverter control used in this study is shown in Fig. 3. It employs dq reference frame-based controls by synthesizing β signals, 90 degree phase shifted from the single-phase quantities (used as α signals) [14]. For current limiting, as illustrated in Fig. 3, the current reference signals, i^*_{dq}, are scaled, if the magnitude of currents, $\sqrt{i_d^2 + i_q^2}$ exceeds the limit, with current angle remaining same.

Single-phase IBRs are, in general, scaled at less than 10 kVA. To recover a sizable community, e.g., a few hundreds of kW, cooperation of multiple single-phase GFM IBRs for a collective black start is envisioned [15]. To represent aggregated dynamics of signle-phase GFM IBRs in an area, a reduced-order aggregate dynamic inverter model is used [16].

B. IBR Interconnection and Load Transformer Model

To simulate transient events in the black-start process, the saturation and hysteresis of transformers are modeled. The magnetizing current is included as part of the saturation. The IBR grid interconnection transformers are modeled in the $\Delta - Y_g$ configuration (0.48-kV Δ to 24.95-kV Y_g) to ensure a reliable grounding source for the microgrids in islanded mode in the absence of a substation [17].

C. Load Model

Loads are modeled as dynamic RL loads with a constant impedance representation for the terminal voltage less than 0.8 p.u. For voltages greater than 0.8 p.u., the loads are modeled as constant power loads.

TABLE I: GFM Inverter Hardware and Control Specifications.

Item	Design Selections
3Φ Inverter	P_{rated} = 1 MVA, V_{rated} = 480 V, L_{f} = 0.15 p.u., C_{f} = 5 p.u.
1Φ Inverter	P_{rated} = 450 kVA (GFM2), 600 kVA (GFM3), 200 kVA (GFM4), V_{rated} = 120 V, L_{f} = 0.15 p.u., C_{f} = 5 p.u.
Inner-loop	$k_{\text{V1C}}^{\text{P}} = 1$, $k_{\text{V1C}}^{\text{i}} = 3$, $k_{\text{I1C}}^{\text{P}} = 0.73$, $k_{\text{I1C}}^{\text{i}} = 1.19$, $k_{\text{V2C}}^{\text{P}} = 1$, $k_{\text{V2C}}^{\text{i}} = 5$, $k_{\text{I2C}}^{\text{i}} = 0.35$, $k_{\text{I2C}}^{\text{P}} = 0.5$
Droop	$k_p = 0.01$, $k_q = 0.05$, $\omega_{\text{n}} = 2\pi \cdot 60$ rad/sec
Current limiter	I_{lim} = 1.5 p.u.

TABLE II: Test Feeder Power Flow and Power Ratings of Single-Phase GFL IBRs.

Location	Power Flow (P and Q)	IBR Capacity
Substation	2.080 MW, 0.464 Mvar	1.95 MW
A-phase	181.8 kW, 39.5 kvar	125 kW
B-phase Seg. 1	150 kW, 45 kvar	200 kW
B-phase Seg. 2	400 kW, 100 kvar	450 kW
B-phase Seg. 3	200 kW, 50 kvar	250 kW
B-phase Seg. 4	350 kW, 100 kvar	300 kW
B-phase Seg. 5	150 kW, 100 kvar	125 kW
C-Phase Seg. 1	150 kW, 50 kvar	150 kW
C-Phase Seg. 2	300 kW, 75 kvar	250 kW

D. Motor Model

Start of motor loads largely differs from one of static loads. To investigate the GFM IBR response to the motor start process with limited current capability, a dynamic model of a three-phase induction motor scaled to represent the motor loads in the entire feeder is used in this study for computational efficiency of the simulation. The motor is equipped with a stator-side breaker to simulate the direct starting process [18].

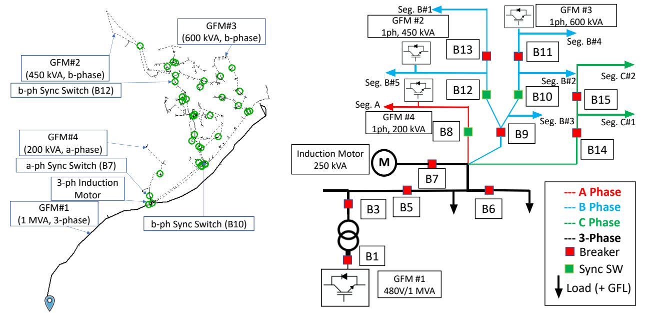
E. GFL IBR Model

Behind-the-meter (BTM) IBRs are modeled as equivalent current sources. The dynamics of a phase-locked loop and power and current control loops are considered for GFL operation, with the inverter dc-side assumed tightly regulated [19]. Real and reactive power set points to the IBRs are set to rated power value and zero, respectively. To aid the black-start process, the BTM IBRs are set to automatically turn on 5 seconds after their terminal voltage reaches close to the rated value. The cooperation of the BTM GFL IBRs in a sequential restoration process would contribute to reducing the GFM capacity required for a successful black start, increasing the chance of wider area recovery with given resources.

III. Simulation Results

A. Feeder Model and Black-Start Scenario

Fig. 4(a) shows a 2-MVA distribution feeder for validation modeled in RSCAD. The feeder is developed based on a real distribution network in western Colorado. Table I lists the inverter parameters. In the feeder, the three-phase GFM, $GFM1$, is interfaced at the medium-voltage side through a dedicated IBR interconnection transformer while the single-phase GFMs, $GFM2$–4, are located at the low-voltage side, directly connected to loads and GFL IBRs. In an outage scenario, $GFM1$–4, each located in a three-phase or single-phase lateral, would energize four individual local microgrids.



(a) (b)

Fig. 4: Feeder for validation: (a) model in RSCAD and (b) simplified network structure.

Afterwards, to merge these local microgrids, synchronization switches are used as noted in Fig. 4, along with controllable breakers to expand areas energized, $B1$–$B15$. A 250-kVA three-phase induction motor (12.5% of the entire loading assumed), GFL IBRs, and three-phase and single-phase residential transformers and loads are also modeled in RSCAD. As noted in Table II, each segment has its own set of local loads, residential transformers, and GFL IBRs.

B. Black Start with Three- and Single-Phase GFM IBRs

The entire RSCAD simulation of the black-start scenario involves both three-phase and single-phase GFM IBRs. Once a blackout is identified and safety procedures are executed for the bottom-up restoration, all GFM IBRs, $GFM1$–4, form local microgrids. In this initial energization process, the three-phase GFM, $GFM1$, soft-starts the grid interface transformer by ramping up the terminal voltage to suppress the transformer inrush current. A similar start-up procedure may be employed for single-phase GFMs in case inrush current is expected, e.g., motor loads, not demonstrated in this simulation. Once the microgrids are formed, each microgrid expands its boundary by closing breakers nearby if it is capable of energizing an additional segment. Since it recovers GFM capability, the GFL IBR involvement in the black-start process facilitate the additional load pick up. In case boundaries of two microgrids meet, a synchronization switch is necessary. The synchronization switch merges the two grids at an instance when the difference between the two voltages is small, which help avoid black start failure by minimizing transients. This passive synchronization can be automated to avoid communication needed and thus to improve system resilience. The synchronization switch monitors the differences in voltage magnitude, frequency, and phase. In case the differences are not acceptable, a secondary control mechanism can be involved to reduce them, e.g., by updating voltage and power set points or controlling loading. The black-start process concludes when all breakers available are closed, i.e., all loads planned for recovery are energized. In the black-start scenario shown in this paper, the breaker closing sequence for the collective black-start is as follows: $B1$, $B3$, $B5$, $B6$, $B11$, $B8$ (sync $GFM1$ with $GFM4$), $B7$ (motor pick up), $B9$, $B12$ (sync $GFM2$), $B10$ (sync $GFM3$), $B13$, $B14$, and $B15$.

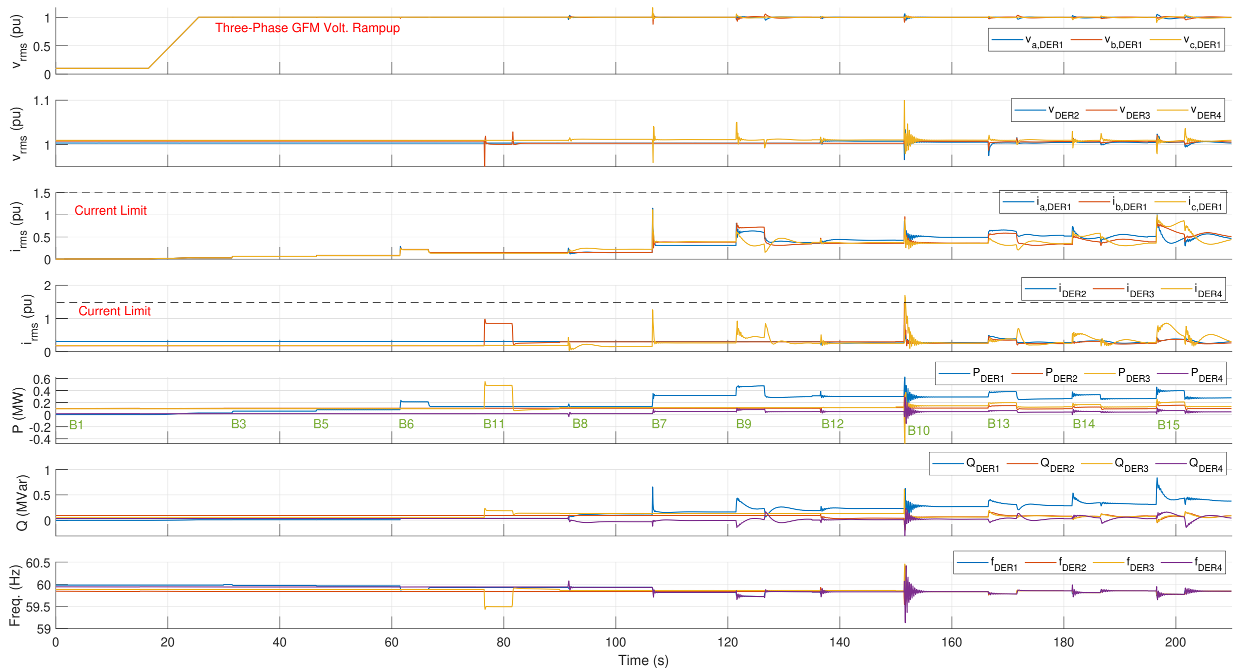


Fig. 5: Entire simulation result: system black-starts using 1 three-phase GFM ($GFM1$) and 3 single-phase GFMs ($GFM2$–4) synchronizing and collectively regulating the system.

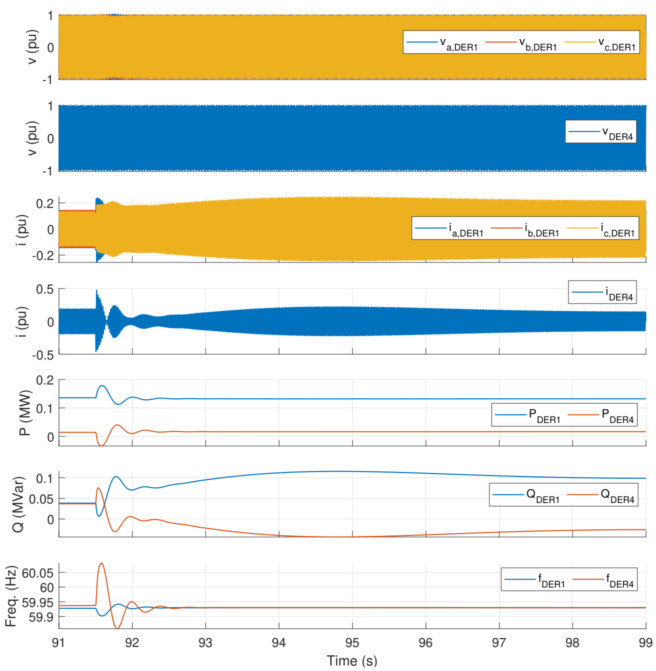


Fig. 6: Microgrids merge with communication-free synchronization. $GFM1$ merges with $GFM4$.

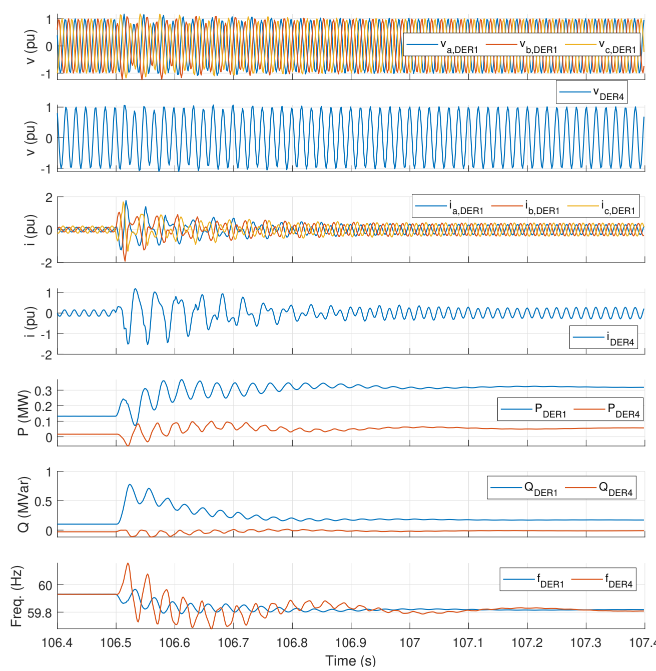


Fig. 7: 250-kVA motor start with $GFM1$ and $GFM4$ sharing the inrush currents.

Fig. 5 displays the results of the entire black-start process. Measurements of the GFM IBR voltages, currents, real and reactive power, and IBR frequencies are shown. Voltages and currents are shown either in instantaneous or rms measurements for clarity. Notable transients are described as follows. The $GFM1$ soft-starts with 0.1 p.u./s voltage ramp, from 16–26s. As shown, the voltage ramp up allows for avoiding a transformer inrush current that might reach 6 p.u.–8 p.u. without a soft start. The first microgrid merge by the synchronization switch, $B8$, is zoomed in Fig. 6. After the initial transients, for a short duration, the oscillations damp out, and the combined network reaches a stable operating point. The successful microgrid merging between a three-phase and single phase GFM IBR is notable.

Fig. 7 shows the transient event of the direct start of a 250-kVA induction motor. The combination of GFMs, $GFM1$ and $GFM4$, collectively provides the high inrush currents required for starting the induction motor, showing the potential of the novel heterogeneous black-start configuration. Majority

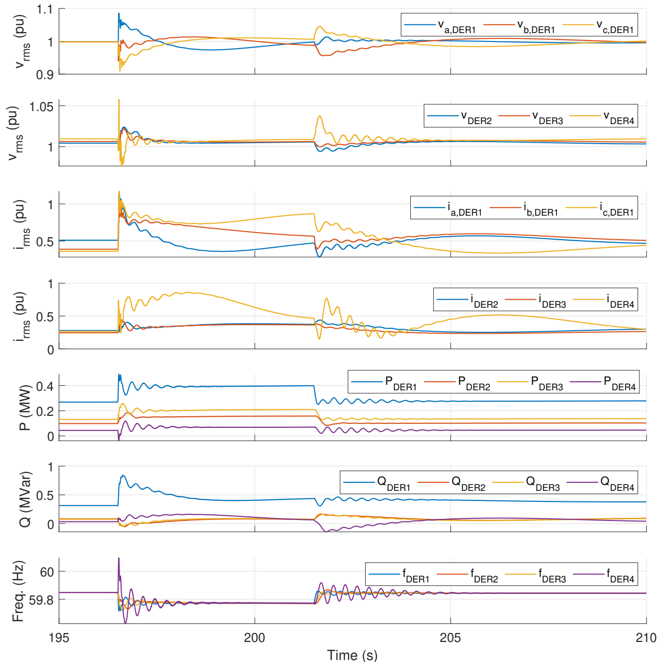


Fig. 8: Final load pickup ($B15$) with all GFMs synchronized and collectively maintaining the unbalanced grid based on the heterogeneous black-start configuration.

of reactive power is provided by $GFM1$ near to the motor, leading $GFM1$ to experience a momentary overcurrent.

Fig. 8 shows the transient of energizing Segment 2 of the C-phase lateral by closing $B15$, the last load pick up. Notable is that though the load transient occurs in C-phase, as the GFMs are all synchronized through the three-phase network, they collectively pick up the load, including $GFM2$ and $GFM3$ in B-phase sharing the burden and settling into new operating points. Fig. 8 also captures the GFL IBRs starting unity power factor injection 5 seconds after their terminal voltages measured recover. As demonstrated, the GFL support would reduce the GFM capacity required for a successful black start by increasing the power headroom of GFM IBRs.

IV. Conclusions and Future Work

This paper investigated the black-start operation of a real-world distribution feeder harmonizing multiple three-phase and single-phase GFM IBRs in EMT simulations. The detailed EMT simulations allowed for evaluating the heterogeneous dynamic system restoration process using advanced GFM inverters with supplementary controls, which are critical for a resilient black start. A negative-sequence voltage control was incorporated with the droop primary control to maintain the feeder voltage balance under unbalanced loading. GFM IBR operation with a phase-current limiter can sustain momentary overloading conditions. In addition, dynamic interaction between three-phase and single-phase GFMs has been investigated. The collective operation of GFM inverters located in different phases and thus successful black start demonstrated present high potential of the heterogeneous black start coordination to achieve extreme resilience. These functionalities would be critical to drive a successful black start with marginally designed or limited GFM resources. Future work includes studies with additional test cases to further investigate dynamic interaction among GFM inverters in different phases, fault scenarios during the black start, hardware validation in a laboratory setup, and field demonstrations.

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