Resilient Inverter-Driven Black Start with Collective Parallel Grid-Forming Operation

Preprint

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Resilient Inverter-Driven Black Start with Collective Parallel Grid-Forming Operation

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***Abstract*—As modern power systems are experiencing exceptional changes with increasing penetrations of inverter-based resources (IBRs), system restoration using IBRs has received attention. Using local grid-forming (GFM) assets near consumers, engineered to establish grid voltages in the absence of a stiff grid, i.e., bottom-up restoration, a distribution system could obtain high system resilience by not relying on the bulk power system restoration, which requires significant human intervention and procedure. This paper studies the technical feasibility of the novel approach with detailed electromagnetic transient (EMT) simulations. To thoroughly evaluate the potential of GFM inverters and the technical challenges in IBR-driven black start, a detailed three-phase inverter model is developed, including negative-sequence control for voltage balance and a phase-by-phase current limiter to sustain momentary overloading during the black start. To examine dynamic aspects of the black-start process, the EMT simulation also models transformer and motor dynamics to emulate their inrush and startup behaviors as well as network dynamics. In addition, active involvement of grid-following distributed energy resources is also studied to facilitate the black-start process. By allowing multiple GFM inverters to collectively black start without leader-follower coordination, we demonstrate that a system can achieve high resilience even with a fraction of assets lost. Two test cases of inverter-driven black start, using two and one GFM inverters, respectively, for a heavily unbalanced 2-MVA distribution feeder are demonstrated. Takeaways for further study and field deployment are provided.**

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

I. Introduction

In recent years, increasing penetrations of inverter-based resources (IBRs), such as solar, wind, and energy storage, have drawn attention toward understanding the potential of using these nonsynchronous resources to provide black-start support, i.e., as black-start resources or kick-starters for a large power plant [1]–[4]. A black-start resource is a generation asset that can start without external support to reestablish a grid. Black-start capability has been exclusively provided by synchronous generator-based power plants [5]. To establish the grid voltage using a power electronics inverter without a preformed voltage from the bulk power system, grid-forming (GFM) inverters are required [6]. One can consider energy storage devices designed with GFM and black-start capability for the inverter-driven black start [7]. Using the quick startup time and fast dynamic performance of the IBRs, a power system can black start and restore supply for its customers, unlocking the path to extreme resilience using local GFM assets [2].

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 (e.g., 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 rated values, making IBRs operate close to their limits [8]. On the other hand, in some cases, inverters can address some issues using their soft-start capability [9], [10]. Additionally, parallel inverter operation should be considered not only to match the baseline loads but also to increase the resilience. 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. In addition, 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]. Regarding voltage regulation using GFM inverters, the authors in [11] proposed a sequence-based control that suppresses the negative-sequence voltage with a phase-based current limiter. Since this method uses an isochronous mode of operation, however, it is not straightforward for a collective IBR black-start application or parallel operation.

This paper contributes to addressing these IBR-related challenges and developing solutions for resilient black starts using GFM IBRs. The key contribution involves multiple GFM inverters in a decentralized manner to achieve a resilient black start. This concept has been proposed in [2], but no detailed investigation is found to evaluate its technological feasibility. To evaluate the potential of the multiple GFM inverter-based black start, this paper develops detailed electromagnetic transient (EMT) simulations. The GFM inverter in the simulation includes a phase-by-phase current limiter for practical implementation and voltage balancing control for unbalanced loading, integrated with the droop primary control, designed to allow for collective parallel GFM operation. In addition, to evaluate the impact of grid-following (GFL) IBRs in a black start, their automated operation after recovery is modeled. In

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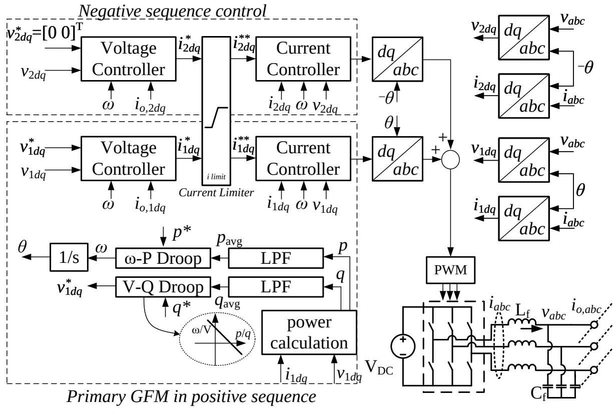

Fig. 1: GFM inverter control diagram including negative-sequence voltage compensation.

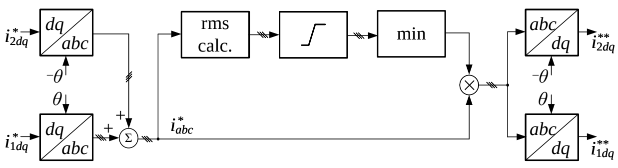

Fig. 2: Phase current limiter for positive- and negative-sequence current controller.

a 2-MVA distribution simulation system, where transformers and motors are modeled to capture their inrush currents, it is demonstrated that a successful black start can be collectively achieved with two GFM IBRs maintaining voltage balance and sharing unbalanced system loading without leader/follower coordination and by not relying on predetermined black-start resources. A single-inverter black start encountering overloading is also demonstrated as an extreme restoration case.

II. EMT Models for GFM Black-Start Study

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

A. GFM Inverter Model

1) Droop-Controlled Grid-Forming Inverter with Negative-Sequence Control: The architecture of the droop-controlled GFM inverter is shown in Fig. 1. It features negative-sequence control integrated with a classical droop control with voltage and current inner-control loops in the dq reference frame. For inverters supplying power to balanced phases, the conventional positive-sequence control might be sufficient; however, since distribution feeders are unbalanced, a negative-sequence control to control the feeder voltage unbalance can be added [11]. The negative-sequence control used in this study has voltage and current control loops, as shown in Fig. 1. For unbalanced feeders, band-stop filters are used to filter the double-line frequency (120-Hz) components in the dq transformation.

2) Phase Current Limiter: For balanced networks, current-limiting control for GFM IBRs can be performed in the dq reference frame [12]. For unbalanced distribution systems and unbalanced fault scenarios, however, the conventional current-limiting method could result in suboptimal performance [11]. To limit currents on each phase, the control architecture shown in Fig. 2 is used in this study [11]. As illustrated, the phase-current limiter operates in the abc domain. It monitors the rms current of each phase, and if it detects an overcurrent in a phase, it scales down the current references based on the most severe phase current:

$$\begin{aligned} I_{ph,ref,lim} &= \kappa_i \cdot I_{ph,ref} \\ \kappa_i &= 1, \qquad\qquad\qquad\quad if\, I_{ph,ref} \leq I_{lim}, \\ \kappa_i &= min(I_{ph,ref}/I_{lim}), \quad if I_{ph,ref} > I_{lim}. \end{aligned} \tag{1}$$

B. IBR Interconnection and Load Transformers

To simulate transient events in the black-start process, challenging to IBRs, the saturation and hysteresis of three-phase and single-phase transformers are modeled. The magnetizing current is included as part of the saturation. The distributed energy resource (DER) 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 [13].

C. Loads

Loads are modeled as dynamic RL loads with a constant impedance representation in cases when the values of the terminal voltage are less than 0.8 p.u. For voltages greater than 0.8 p.u., the loads are modeled as constant power loads. This modeling approach helps to have an accurate representation of the overall distribution feeder during a black start and normal operation.

D. Motor Model

A fraction of the total load at the distribution level are motor loads. The black start of motor loads has a largely different response from the black start 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 [14].

E. GFL BTM IBR

In this paper, 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, with the DC-side dynamics ignored [12]. Real and reactive power set points to the DERs 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. This active contribution from the BTM IBRs coupled with a sequential restoration process would contribute to keeping the GFM capacity required for a successful black start low, increasing the chance of recovery with given resources.

III. Simulation Results

A. Feeder Model and Black-Start Scenarios

Fig. 3(a) shows a 2-MVA distribution feeder and two utility-scale 750-kVA GFM DERs (DER_n and DER_a) along with the three-phase backbone for validation. RSCAD is used in

TABLE I: GFM Inverter Hardware and Control Specifications.

Item	Design Selections
Inverter parameters	P_{rated} = 750 kW, V_{rated} = 480 V, L_{f} = 0.15 p.u., C_{f} = 5 p.u.
Inner-loop control	$k^{\text{p}}_{\text{V1C}}$ = 1, $k^{\text{i}}_{\text{V1C}}$ = 3, $k^{\text{P}}_{\text{I1C}}$ = 0.73, $k^{\text{i}}_{\text{I1C}}$ = 1.19, $k^{\text{P}}_{\text{V2C}}$ = 1, $k^{\text{i}}_{\text{V2C}}$ = 5 $k^{\text{i}}_{\text{I2C}}$ = 0.35, $k^{\text{P}}_{\text{I2C}}$ = 0.5
Droop	k_p = 0.005, k_q = 0.075, ω_{n} = $2\pi \cdot 60$ rad/sec
Current limiter	I_{lim} = 1.5 p.u.

TABLE II: Test Feeder Power Flow and Single-Phase DER Information.

Location	Power Flow (P and Q)	DER 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

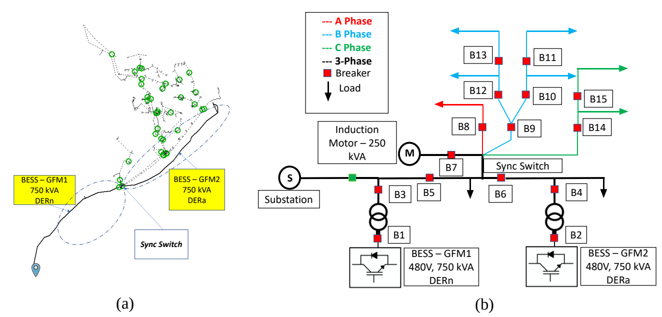

Fig. 3: Feeder for validation: (a) model in RSCAD and (b) equivalent network.

this study. The feeder itself is modeled based on a real distribution network in western Colorado. Table I lists the inverter parameters. In an outage scenario, DER_n and DER_a would energize local microgrids, and to merge these local microgrids, a synchronization switch, $B6$, is used. The feeder also consists of several other three-phase and single-phase breakers ($B1$-$B15$), a 250-kVA three-phase induction motor (12.5% of the entire loading assumed), BTM DERs, and three-phase and single-phase residential transformers and loads, which are not shown in the simplified diagram. Each segment separated by the breakers in the feeder has its own set of local loads, residential transformers, and DERs. Table II shows the load energized in each segment and the BTM DER capacity.

B. Case 1: Black Start With Parallel Operation of GFM IBR

In Case 1, both GFM DERs are used in parallel. The two droop-controlled GFM assets individually energize local areas, as marked by the two regions in Fig. 3(a), forming two local microgrids. In this initial energization process, the GFM IBRs soft-start the grid interface transformers by ramping up the output voltage to minimize the transformer inrush current. Once the microgrids are formed, the synchronization switch merges the two grids at an instance when the difference between the two voltages is small to suppress the transient,

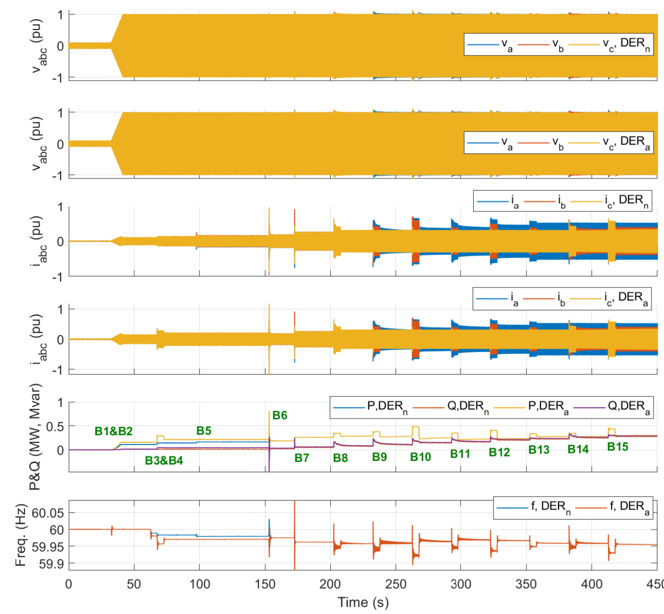

Fig. 4: Entire simulation results of Case 1: collective black start using two GFM DERs.

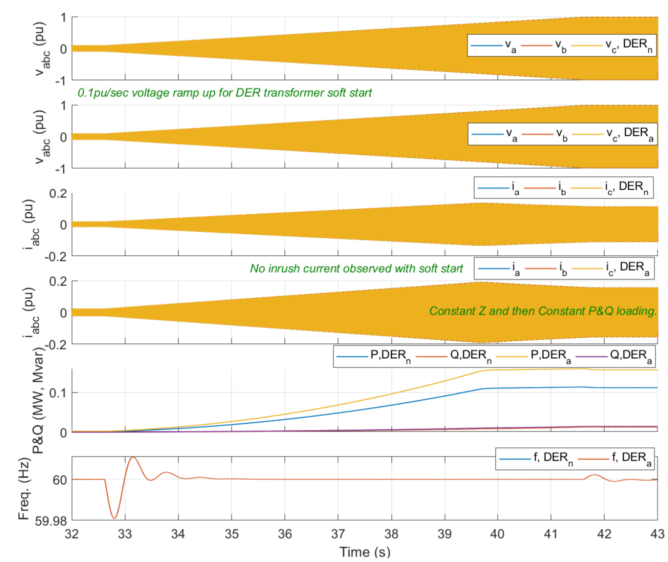

Fig. 5: GFM voltage ramp-up for transformer soft start in Case 1.

automated operation once enabled without communication. Following the merge, the rest of the network, including the three-phase induction motor and the single-phase laterals, are recovered. The breaker closing sequence used for the collective black-start process is as follows: $B1$&$B2$, $B3$&$B4$, $B5$, $B6$ (sync switch), $B7$ (motor breaker), $B8$, $B9$, $B10$, $B11$, $B12$, $B13$, $B14$, and $B15$.

Fig. 4 displays the results of the entire black-start process. Measurements of the GFM IBR voltages, currents, real and reactive power, and DER frequencies are shown. Due to space constraints, only key transient events are discussed further. Fig. 5 displays the DER transformer soft start with the voltage ramp. As shown, the voltage ramp up allows for avoiding an inrush current that might reach 6 p.u.–8 p.u. without a soft start. Final currents are determined by the local auxiliary loads of the GFM IBRs. The microgrids' merge by the

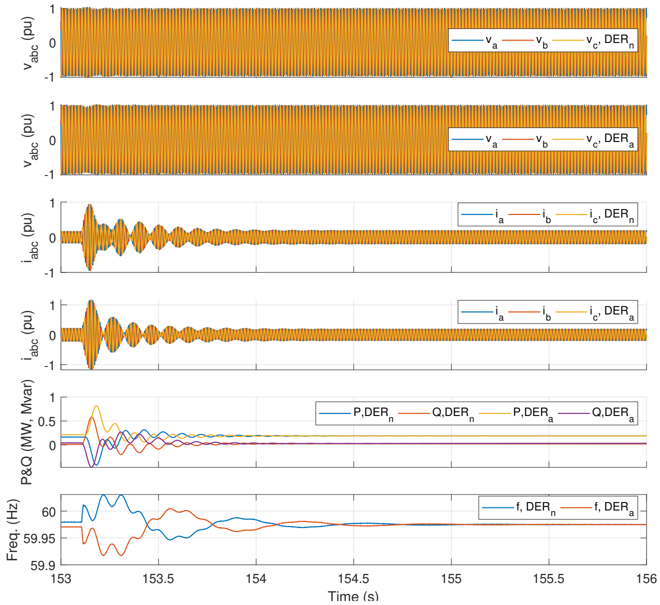

Fig. 6: Microgrids merge with communication-free synchronization in Case 1.

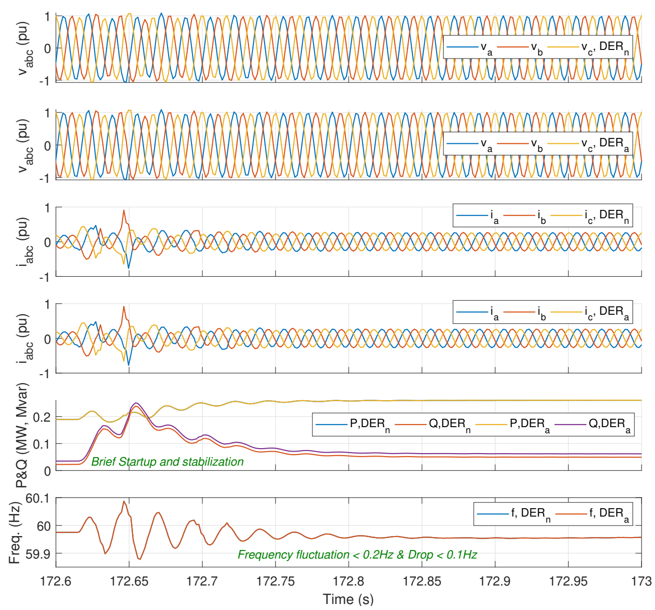

Fig. 7: 250-kVA motor start in Case 1.

synchronization switch is captured in Fig. 6. After the initial transients, for a short duration, the oscillations damp out, and the resultant network reaches a stable operating point, without communication. The conventional droop-controlled GFM IBR-sourced networks have been known to reliably merge; however, the successful microgrid merging using GFM DERs with negative-sequence compensation is noteworthy. Fig. 7 shows the transient event of the direct start of a 250-kVA induction motor. The two GFM DERs, now merged, quickly provide the high reactive power required for starting the induction motor, fairly sharing the burden. Fig. 8 shows the transient of energizing Segment 2 of the B-phase lateral by closing breaker $B10$. As shown, even with the unbalanced nature of the downstream load, the DER terminal voltages remain

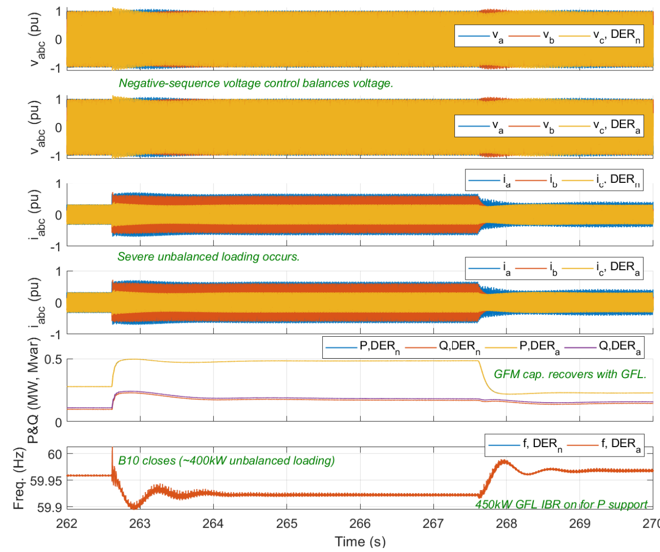

Fig. 8: Energizing B phase Segment 2 in Case 1. At 262.6 seconds, $B10$ closes, and at 267.6 seconds, the DERs in the segment start injecting power.

balanced by the negative-sequence control, and the segment is energized in a stable manner. Also, at $t = 267.6$ seconds, the BTM GFL DERs are energized, 5 seconds after their terminal voltage is reestablished. As demonstrated, the GFL support would help reduce the GFM capacity requirements for a successful black start.

C. Case 2: Black Start With a Single Overloaded GFM IBR

In Case 2, only one GFM IBR, DER_n, is involved for a black start of the same test feeder. This is to investigate the potential of an inverter-driven black start in a resource-limited condition due to the unavailability of some resources resulting from natural disasters or cyberattacks. Under such conditions, black-starting inverters might encounter overloading that could cause an instability and/or black-start failure. The black-start sequence follows the same steps as Case 1 except that breakers associated with DER_a are not involved. The entire black-start process is captured in Fig. 9, with corresponding breakers for transients noted for clarity. Notable steps are discussed. Fig. 10 captures the transient of the 250-kVA induction motor direct start. As shown, this step forces the single GFM IBR to reach the current limit due to the significant reactive power demand in the motor start. Note that the inverter terminal currents exceed the limit (1.5 p.u.) for a brief moment, but the current limiter quickly restricts each phase current under 1.5 p.u., proving the effectiveness of the current-limiting strategy. Since the limited current capability restricts the flow of reactive power to the motor, as a result, the time taken for the flux to develop increases, by roughly 1 second. Note in Case 1 that it takes roughly 0.5 second, as shown in Fig. 7. This shows a delayed but stable motor start operation with reduced GFM IBR capacity. Also, it is noticed that the frequency fluctuation and oscillation are increased due to the limiter interaction with the primary control.

Similar to Case 1, the sequential single-phase lateral energization follows. As shown in Fig. 9, the single GFM DER

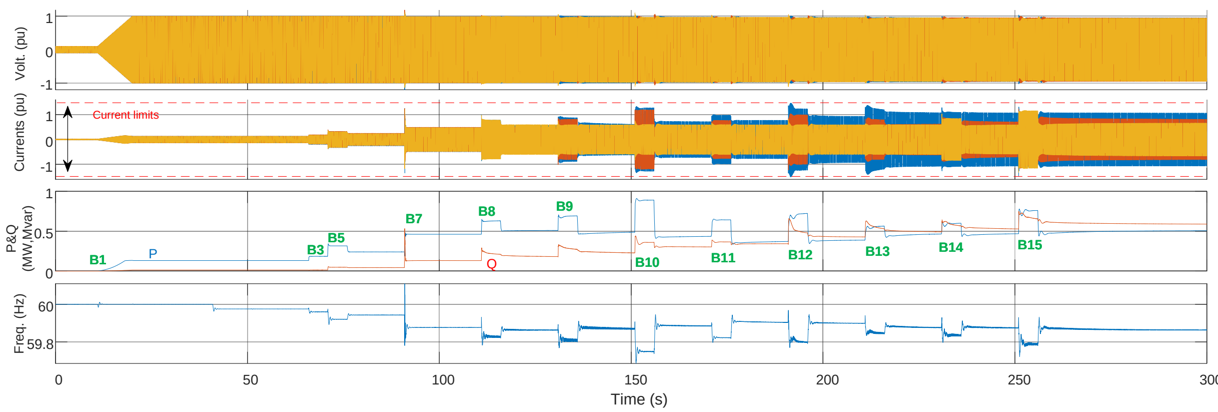

Fig. 9: Entire simulation results of Case 2: black start using a single GFM DER.

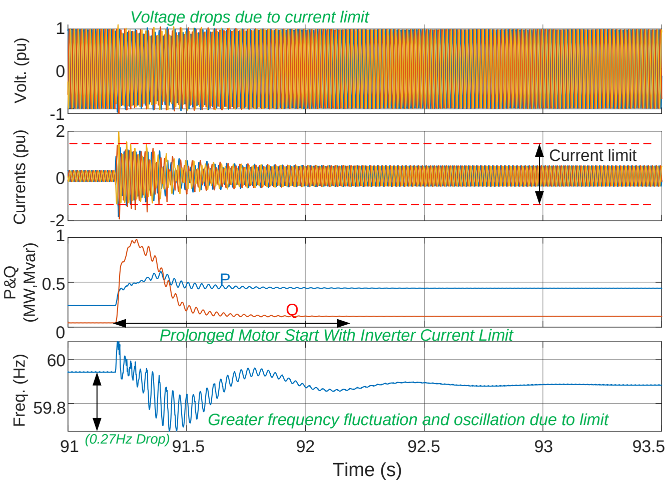

Fig. 10: Motor startup using single GFM ($B7$ closes) in Case 2.

manages to recover laterals one by one with increased transient responses due to higher loading. It is also noted that the timely support from the GFL assets largely reduces the burden on the GFM asset, enabling a swift system recovery within 5 minutes.

IV. Conclusions and Future Work

This paper investigated the black-start operation of a real-world distribution feeder using GFM IBRs with EMT simulations. The detailed EMT simulations allowed for evaluating the 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 in the abc frame to overcome momentary overloading conditions was also demonstrated. This functionality would be critical to drive a successful black start with marginally designed or limited GFM resources. The effect of the voltage ramp up to suppress the inrush current of the DER grid-interface transformer was also shown. The two test cases with varying numbers and capacities of GFM assets demonstrated reliable black-start operation using IBRs. In addition, they demonstrated the potential benefit of the cooperative operation of GFL assets in a black start that would facilitate the system recovery, reducing the GFM capacity required. Future work includes studies with additional test cases, such as fault scenarios during the black start, hardware validation in a laboratory setup, and field demonstrations.

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