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Idaho National Laboratory

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Black Start with Inverter-Based Resources: Hardware Testing

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***Abstract*— Black start, or grid restoration after a wide-spread power outage, is a critical service on the power system that has historically been provided by transmission-connected synchronous generators. As the power system transitions to rely on more distributed and inverter-based resources it will be critical that these resources can also provide black start services. In this work we investigated battery energy storage and solar photovoltaics technical capabilities and limitations to provide black start services through hardware testing in an experimental microgrid testbed. This hardware demonstration of inverter-based resources providing black start functions can help inform grid operators on how to include these types of resources in their black start plans.**

Index Terms – black start, distributed energy resources (DER), energy storage, inverter-based resources (IBR), power system restoration

I. Introduction

A. Black Start in the Bulk Power System

Black start is a critical service to restart the power system after a wide-spread outage that is traditionally provided by transmission-connected synchronous generators. Specific requirements vary by region but generally for a power plant to be designated as black start capable, it must have reserve power on-site to provide startup and controls power to the plant while islanded, sufficient real and reactive power capacity to energize the necessary transformers, lines, and customer loads which it is specified to start, and reserved energy capacity (or fuel storage) to operate for the duration specified by the grid operator. In addition, plants with minimal start-up time are desirable [1].

B. Need for Utilizing New Resources for Black Start

Our electricity grid is transitioning to rely more heavily on inverter-based resources (IBRs), such as solar, wind and battery, rather than synchronous generators [2], a trend that is expected to accelerate due to the low cost of solar and wind and government incentives like the production and investment tax credits included in the Inflation Reduction Act [3]. In 2021, around 13% of electricity generated in the US was from solar and wind resources [2] with higher percentages in certain regions. Energy storage is also being added to the grid at a rapid pace [4], in part to balance the intermittency of renewable sources, and is well positioned to provide ancillary services, such as black start. While renewables are being added to the electricity grid, synchronous generators are being retired. In 2022, about 15 GW of synchronous generators are planned for retirement, the majority of which are coal plants [5]. As inverter-based generators replace synchronous generators in the power system it is critical that we maintain black start capability with the new mix of available resources on the power grid.

C. Challenges for Inverter-Based Resources Providing Black Start Services

There are a few challenges related to utilizing IBRs in black start, including technical differences between the behavior of inverter-based and renewable resources, economic constraints, power system architecture and control requirements. All IBRs have less over-current capacity than similarly sized synchronous generators which can affect their ability to black start high in-rush current loads, like motors and transformers, and limits their fault current contribution [6]. Renewable IBRs have intermittent supply which limits their ability to always be available for black start services, while energy storage IBRs must balance the economic cost of maintaining energy reserve for low probability black start events with using that energy for other services [1],[6]. While traditional black start resources are large and centralized, battery and solar resources are often distributed and distribution-connected, which changes the operational strategy for utilizing them as black start resources and likely requires paralleling of multiple IBRs. Grid-forming control modes are required on IBRs to directly provide black start services. Multiple studies have been conducted to simulate power system behavior during power restoration operations with the deployment of grid-forming inverters [6]-[8]. However, most of these studies do not include simulation verification through hardware testing in a real power system. In this work we aim to validate the use of IBRs for black start through hardware testing, documenting the performance under different scenarios

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and demonstrating how IBRs can work together to black start a system.

D. *Current State of the Art for Inverter-Based Resource Black Start*

There are many ways in which IBRs could be integrated into support of a black start event, with studies covering a range of options and some limited examples of field deployment of these strategies. In a supporting role, the flexible control and fast response of IBRs could assist in stabilizing the grid frequency during a black start sequence where the lead black start units are conventional synchronous power plants [9]. One benefit of IBRs is the ability to operate stably at lower percentages of total rated power. This attribute can give system operators more flexibility in how they step load up during the black start sequence than in a case with only synchronous generators. An alternative supporting role for IBRs in black start is to provide auxiliary power (or kick-start power) for a larger synchronous generator. For example, there is a natural gas fired power plant in the Imperial Irrigation District in Southern California that has demonstrated the use of a co-located battery energy storage system (BESS) to provide kick-start power to the main plant [10].

IBRs could also play a more direct role in black start functions by providing initial cranking power and frequency and voltage support to the grid. This approach could follow the top-down approach of current black start units, where transmission connected IBRs provide black start services, or a more distributed approach where distribution-connected IBRs form islands within the distribution system that are then synchronized and connected to one another to restart the system from the bottom up. Both approaches have been studied in simulation and Hardware-In-the-Loop (HIL) environments [11] with findings indicating that the over-current capability challenge can likely be overcome if equipment is properly sized and in-rush current limiting techniques, such as soft start, are employed [6]. The Distributed ReStart project in Great Britain has demonstrated a bottom-up approach to power restoration with distributed energy resources using a Real Time Digital Simulator (RTDS) and live testing. In one of the live tests a wind farm successfully energized 132kV and 275kV transmission system assets with grid-forming inverters [12], [13]. Black start with BESS in a medium voltage distribution system is also demonstrated in [14] which focuses on development of controls strategies to limit in-rush current.

The contributions of this paper include hardware testing-informed discussion on the technical capabilities, limitations, and order of operations for utilizing IBRs for black start. There are limited examples of commercial hardware testing of inverter-based resources performing grid-forming functions currently in the literature. To fill this gap this paper includes testing comparisons between diesel generators and BESS with solar photovoltaics (PV) performing black start. Testing utilizes commercially available controls and investigates different load types as well as switching procedures. Demonstration of grid-forming device synchronization is also shown.

II. Test Setup

Hardware testing was conducted on an experimental microgrid with grid-forming BESS, solar PV, and diesel generators. The microgrid testbed includes low voltage connections at 120V, 208V, and 480V and medium voltage lines at 13.2kV. Measurements of 3-phase voltage and current were taken at all sources and most loads with power meters recording continuous 60Hz Phasor Measurement Unit (PMU) data and 1kHz event-triggered data. For limited tests a four-channel oscilloscope with 2 voltage and 2 current inputs was used for higher resolution data capture. Figure 1 shows the full configuration of the microgrid under test including subcomponent power ratings. Control of loads, which varied between tests, was done manually and control of sources utilized the existing commercial-off-the-shelf device-level controllers. Commands to the BESS such as operating mode, nominal setpoints and on/off commands were sent over a REST interface by the test operator. The grid configurations such as how much of the microgrid was connected and through which lines (overhead or underground) also varied between test cases.

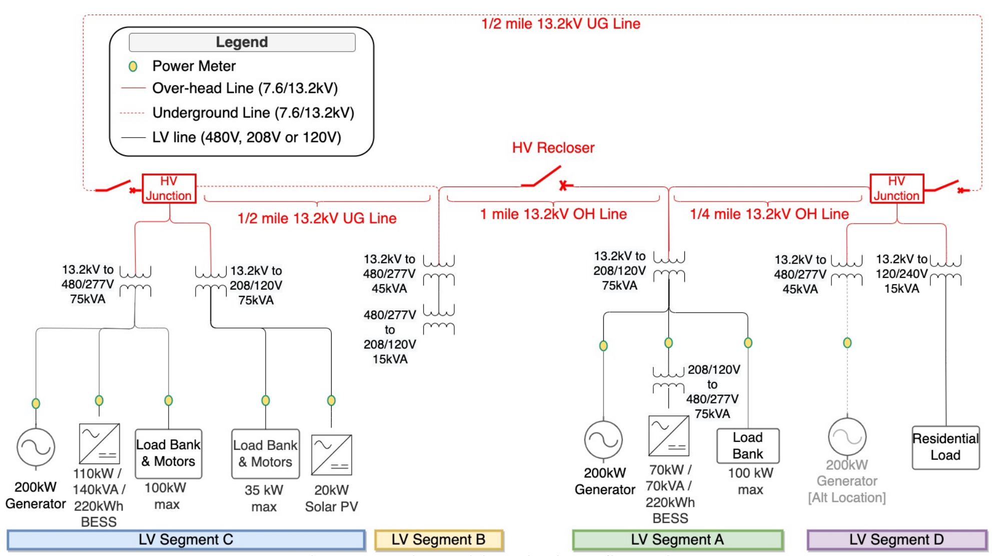

Figure 1: Microgrid testbed configuration

Finally, the type and number of sources connected to the microgrid varied between test cases. The following section describes the unique configuration and results for each test case.

III. Test Results

Test results related to battery black start capability and grid-forming battery synchronization are presented in Sections III.A and III.B, respectively.

A. Black Start Capability

In this section, key findings about the grid-forming battery's capability to black start the system under a variety of conditions are presented. We consider the diesel generator black start capabilities as the base case. The base case, shown in Figure *2*, is black start from a 200kVA diesel generator in low voltage (LV) Segment C with the HV recloser in the closed position. The black start source energizes over 1.75 miles of medium voltage line, over 400kVA of transformer capacity and the load bank in Segment C which is set to 10kW.

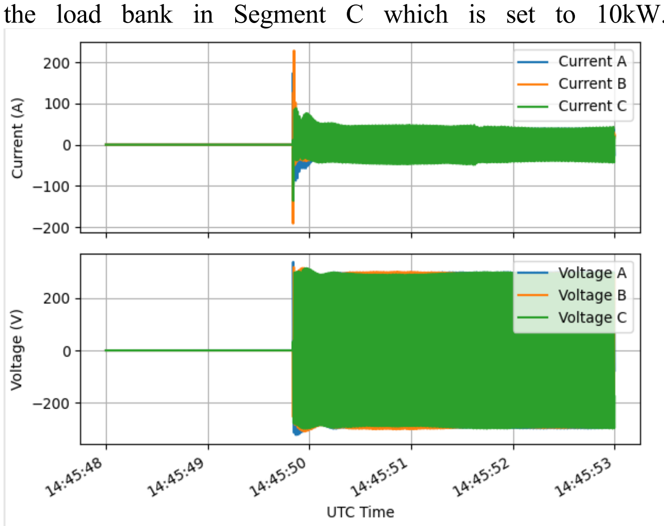

Figure 2: Successful diesel generator black start from LV segment C

1) Transformer Energization with Grid-Forming Battery

To address the technical challenges as described in Section I.C, the in-rush current capability of a grid-forming battery is explored. In the first test a 110kW/140kVA battery in LV Segment C, black started the same microgrid system described in Section III.A. Figure 3 shows that the battery can successfully black start a system where the transformer capacity exceeds the black start source power rating by over 3:1. In this test, the battery uses a soft-start, or slowly ramps voltage to limit in-rush current, taking multiple seconds to reach nominal voltage. The diesel generator black start shown in Figure 2 has a more immediate approach (the generator fully starts up with its output contactor open and then closes the contactor which applies voltage to the de-energized segment almost instantaneously). The peak current during the battery black start was less than 70A, compared to over 200A during the generator black start. The load bank setting was low during this specific test, but further testing showed a battery black start load limit of about one third its rated power at 0.8 power factor. Another point of comparison between the sources is the total harmonic distortion (THD) which was higher during the battery black start (8.3% voltage THD, 61.3% current THD) than during the generator black start (6.2% voltage THD, 36.2% current THD).

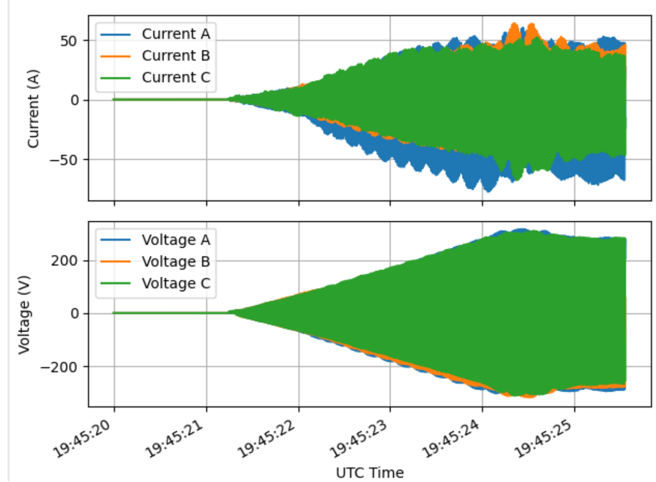

Figure 3: Successful battery black start from LV Segment C

While the soft-start approach of the battery was very effective in energizing the transformer load within the microgrid, there could be use cases where soft start is neither desirable nor feasible. The following test case aims to measure the battery's performance in the case where soft start cannot be performed and it looks more like the diesel generator black start. We call this the "hard switch" test case, and in it we disconnected the battery from the rest of the microgrid at the low voltage disconnect switch. Then, we commanded the battery to turn on in grid-forming mode such that it was only energizing the system up to the open disconnect switch. Finally, we manually closed the disconnect switch to apply voltage from the battery to the de-energized microgrid almost instantaneously (like the diesel generator closing its output contactor). In this test case there was similar total load on the system to the test described in Section III.A. Figure 4 shows the current from the battery in LV Segment C during this successful hard switch of the microgrid. The peak current from the battery during the hard start was around 350A, compared to only 70A in the soft-start approach. This test was repeated with a larger resistive load on the system (100kW) and the battery was

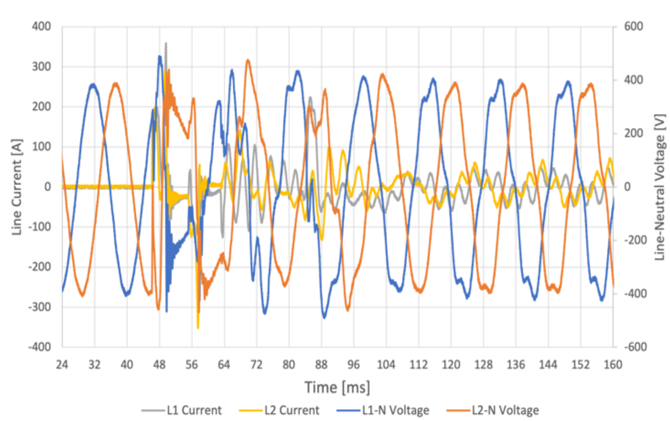

Figure 4: Initial energization current and voltage during successful battery hard switch black start

unable to hard switch the microgrid infrastructure with this additional load.

2) Motor Loads

To demonstrate the capability of the battery to start more diverse loads, a 20hp NEMA design type B motor with automatic start functionality is connected in LV Segment C in addition to 2 more motors of the same type with a combined rating of 30hp. Figure 5 demonstrates the slow voltage ramp of the battery in Segment C black starting, and after time 20:45:39 (UTC), the controller on the motor allows it to start up, leading to a jump in current and temporary drop in voltage. After a few seconds stability is achieved and the additional motors are successfully started up (not shown).

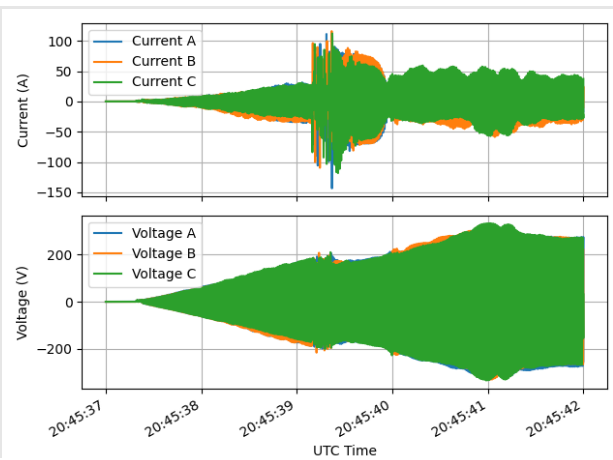

Figure 5: Successful Battery Black Start of Motor Loads

3) Solar PV Response during Black Start

During black start load is added to the system incrementally, so after the black start source provides initial startup power to the system it is required to provide additional power for each incremental increase in load. Solar PV is typically grid-following so it cannot be used in the initial system energization, but it can support these load increases. In our testing there are three single-phase residential solar inverters on phases A, B and C. The phase A inverter had relaxed grid code settings that permitted wider range of operational voltage and frequency. Phase B and C inverters had default grid code settings from UL1741-2016. Figure shows the phase A inverter (with wider trip settings) riding

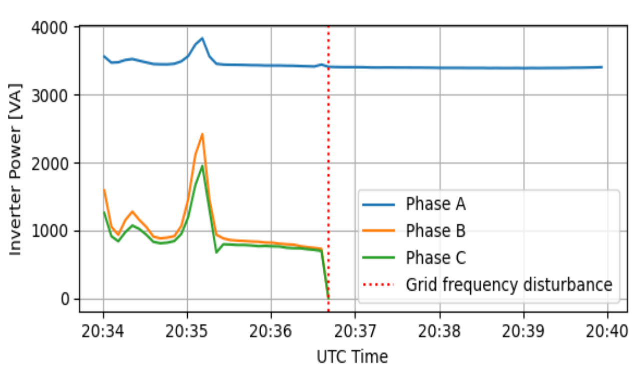

Figure 6: Solar Inverter Ride Through During 100kW Load Step

through a load step of 100kW (at 20:36). During the transient caused by the 100kW load step, phase B and C inverters tripped on 'grid frequency disturbance,' while the phase A inverter continued to operate. We found that the battery could adjust to load steps as large as its rated power and the solar PV inverters could ride through these transients, but their ride through performance depended on their grid code settings. Grid-following and grid-forming inverters can perform well in parallel and are capable of riding through significant system transients, but trip setting tuning is important.

B. Synchronization

As small segments of the system are reconnected in black start operations, it is common to need to synchronize and connect isolated grid segments or islands. To explore this requirement, we demonstrated the capability of isolated microgrids with BESS acting as sources to synchronize and operate in parallel. In this test case two islands are created: one consisting of LV Segments B and C (referred to as Island C) and one consisting of LV Segments A and D (referred to as Island A), separated by a smart recloser (with synchronization check capability) on the 13.2kV line. Each island contains a battery in grid-forming mode. The islands can be reconnected through the HV recloser by enabling the device to close if the synchronization requirements are met or by forcing the device to close "out of sync."

To enable a synchronized close (Figure 7) the frequency set points on each grid-forming battery were adjusted until the synchronization criteria was achieved and the recloser closed. Both batteries rode through the switch closing event with even power sharing after the transient. During an unsynchronized close (Figure 8), where the voltage phase angle difference was 15 degrees and the voltage magnitude difference was approximately 0.015pu, current transients are higher but both batteries still rode through. The current waveforms during both tests show the phase-by-phase closing of the recloser contacts. The forced synchronization test shows a larger disruption with about twice the peak current. These tests demonstrate that IBR-formed islands can be combined or re-integrated with the larger power system without tripping or loss of load.

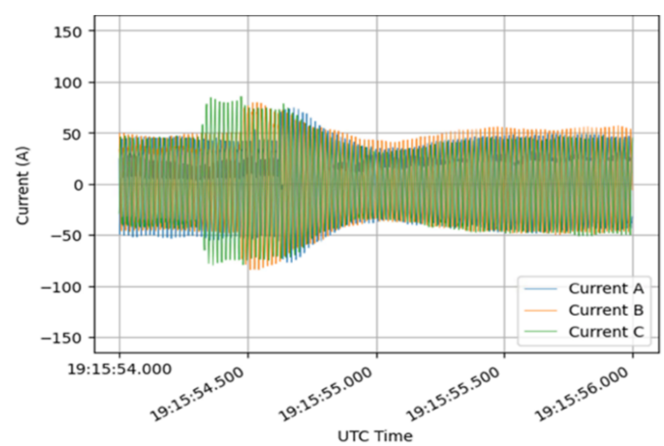

Figure 7: Current from battery in LV Segment C during a synchronized close between two islands

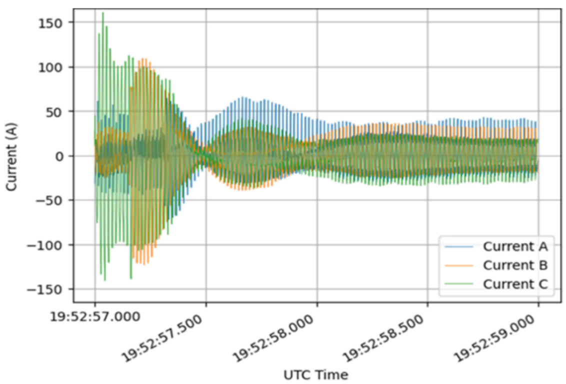

Figure 8: Current from battery in LV Segment C during a forced (unsynchronized) close between two islands

IV. Discussion

Through real hardware testing, we have shown that inverter-based BESS systems are capable of black starting a variety of load types including transformers and motors. A single grid-forming battery was able to black start many load types, including microgrid infrastructure shown in Section III.A.1 (medium voltage lines and transformers rated three times the kVA rating of the battery inverter) and motor loads shown in Section III.A.2 up to 50 horsepower (hp). Soft start strategies can be employed to limit in-rush current of black started loads. However, this would require having high in-rush current loads connected to the BESS during its initial startup, which might require different order of operations for switching than is typical. We observed that the BESS was able to stably handle load steps as high as its rated power when in grid-forming mode, but could only black start a load up to about one third of its rated power. This would indicate that adding large load segments after battery has performed initial black start is feasible. We also found that grid-following solar PV could stably join the grid formed by the BESS system and support a restoration process. Finally, we found the grid-forming batteries in islanded systems could be combined through a recloser with synchronization check indicating that connecting islands during a bottom-up black start approach may be feasible.

V. Conclusion

Through hardware testing, we demonstrated the capabilities of a grid-forming BESS and grid-following solar PV to provide grid restoration services within an experimental microgrid testbed. We found that the battery was able to black start a variety of load types and sizes, including motor loads, and solar inverters with wide trip thresholds could ride through most transients to provide additional capacity. However, when comparing the battery system to a diesel generator of similar power rating, the diesel generator could provide more in-rush current and is therefore capable of starting larger loads directly. Multiple grid-forming IBRs can be used to create smaller microgrids, which can then be synchronized and connected to perform a distributed black start as opposed to the traditional "top down" approach, which could also enable faster restoration to local loads. This work shows promise that inverter-based resources can be used for black start services. Further hardware testing could expand the size and variety of devices under test to ensure similar performance is possible in a larger and more diverse system.

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