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Analysis and Application of Grid-Forming Battery Energy Storage System for Reliability Improvement on the Eversource Distribution System in Cape Cod Massachusetts

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SUMMARY

This paper presents a unique application of the grid-forming inverter technology to improve the reliability of the Eversource's distribution system in Cape Cod, Massachusetts. The area transmission and distribution systems are radial and vulnerable to disruption by severe coastal weather and local faults. The battery energy storage system (BESS) in Provincetown, MA went into service in 2022 to increase the system resiliency. If the transmission or distribution supply to the area is disrupted, the BESS will transition from the grid-connected mode to the islanded mode seamlessly and serves the area load. The project is one of the first and largest worldwide deployments of the grid-forming inverter technology in an interconnected system.

The Provincetown BESS is 25 MW/38 MWh/57.6 MVA, and it is connected to the Eversource 23 kV sub-transmission system. It includes sixteen 3.6 MVA power conversion systems. Due to long and radial transmission and sub-transmission circuits in the area, the short circuit strength at the project point of interconnection (POI) is very low. The grid-forming capability allows the BESS inverters to ride through disturbances despite being at an ultra-weak POI on the system. Under the islanded condition, the BESS operates as the primary source in the microgrid, i.e., it forms the grid; Other grid-following inverter-based distributed energy resources connect to the islanded system formed by the BESS. Under both grid-connected and islanded conditions, the BESS inverter operates in the grid-forming mode using the frequency droop control scheme. The BESS also provides voltage support and peak load shaving functionality during the normal grid-connected condition. It also has black-start capability.

Comprehensive electromagnetic transient (EMT) analysis was performed to ensure control system stability and the adequacy of the inverter's ride-through capability. The BESS inverter EMT model used in the analysis was provided and validated by the inverter manufacturer and uses the actual firmware control code. Due to the weak grid condition at the project POI, the frequency and the voltage droop settings and the maximum fault current contribution of the

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inverter were adjusted to ensure control system stability during and after disturbances. With these changes, the inverter can ride through transmission and fairly long distribution system faults and transition from the grid-connected mode to the islanded mode seamlessly when needed.

In addition to the use of the grid-forming inverter, the project uses a novel control and protection strategy. Several reclosers with communication capability are installed on the 23 kV circuit to which the BESS is connected. The reclosers communicate with each other to locate faults on the circuit and isolate the smallest part of the circuit needed for fault clearance. Based on the identified system conditions, the BESS controller, the microgrid and distribution automation controllers reconfigure the microgrid automatically and minimize the load loss on the 23kV distribution system. The protective devices have different settings for grid-connected and islanded conditions. Hardware-in-the-loop testing using the RTDS verified the desired operation of relays, the distribution automation controller, and the BESS management system.

KEYWORDS

Battery Energy Storage System, Electromagnetic Transients, Grid-forming Inverter, Microgrid, Weak Grid, Black Start, Power Grid Resilience, Islanding, Frequency Droop Control

1. INTRODUCTION

This paper presents the Provincetown grid-forming (GFM) Battery Energy Storage System (BESS) project installed to improve the reliability of a segment of Eversource's at-risk distribution customers in Cape Cod, MA. The BESS not only performs voltage support and peak load shaving functionality during the normal grid-connected condition but also is able to form an island in the event of certain transmission and distribution contingencies to continue to serve load connected to a sub-transmission system.

A GFM inverter is a novel type of inverter that provides a viable solution for the technical challenge of stable operation of the bulk power grid with large share of inverter-based resources (IBR) [1]. Since grid-following (GFL) inverters need an externally regulated voltage source with steady voltage magnitude and frequency, it is not possible to operate the grid with high penetration of GFL IBRs. In contrast, a GFM inverter behaves as a voltage source behind an impedance [2] creating its own voltage and frequency reference.

The concept of the GFM inverter is being evolved by the research community considering the needs of the grid of the future with significant integration of inverter-based renewable resources [3]. There has been various academic works and a few industry deployments over the past few years. In [3], the authors describe the GFM inverter functionality for secure grid operation with high penetration of inverter-based resources. Reference [4] studies the control strategy of a microgrid that uses a GFM battery energy storage system. Reference [5] derives a high-level definition of GFM inverters for a power system with 100% power electronics devices and evaluates the technological aspects of designing a GFM source with voltage source converters. Reference [6] presents the design and functionality of a virtual synchronous machine GFM inverter installed in South Australia. In [7], the authors present a synchronization control technique for a GFM inverter operating in a microgrid to improve the transients during transition between grid-connected and islanded modes.

Several factors led to the selection of a GFM inverter for this project largely due to the radial system characteristic of the study area. For example, the BESS was expected to serve load under the islanded condition, as well as provide necessary black start capability. Unlike GFL inverters, GFM inverters have the capability to perform both of those functions. Furthermore, the short circuit strength at the project's point of interconnection (POI) is very low. As this study demonstrates, GFM inverters can operate stably under ultra-weak grid conditions unlike GFL inverters, which could face control instability after a disturbance in a weak system. Voltage source behavior of a GFM inverter also allows for seamless transition from the grid-connected mode to the islanded mode, i.e., the inverter power output matches the load after the island is formed instantaneously.

A GFM inverter can maintain stability provided that the system to which it is connected can handle its active and reactive power injection. Due to the weak grid condition at the project POI, the frequency and the voltage droop settings and the maximum fault current contribution of the inverter were adjusted to ensure control system stability during and after disturbances. With these changes, the inverter can ride through transmission and fairly long distribution system faults and seamlessly transition from the grid-connected mode to the islanded mode when needed.

The remainder of the paper is structured as follows. Section 2 provides the background information about the project including the system characteristics near the project POI and the GFM control strategy of the BESS. Section 3 describes the electromagnetic transient analysis performed to evaluate the project fault ride through (FRT) performance and parameter adjustments made to ensure inverter control stability. Section 4 presents the BESS operation data. Section 5 presents the conclusions and future work.

2. PROJECT BACKGROUND

The 25 MW/38 MWh/57.6 MVA grid-forming BESS is connected to the Eversource 23kV sub-transmission system in Provincetown, MA. It includes sixteen 3.6 MVA power conversion systems. Due to long and radial transmission and sub-transmission circuits in the area, the short circuit strength at the project POI is very low. The short circuit ratio is 0.7, which indicates that the voltage stiffness at the POI is low. The BESS can operate under both grid-connected and islanded conditions. Figure 1 shows the area transmission and sub-transmission systems near the project. Figure 2 shows the one-line diagram of the area sub-transmission system. Figure 3 shows the battery modules and the aerial view of the BESS building.

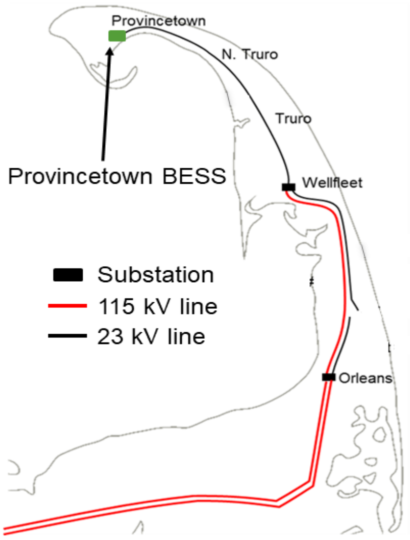

Figure 1. The transmission and sub-transmission system near the Provincetown BESS

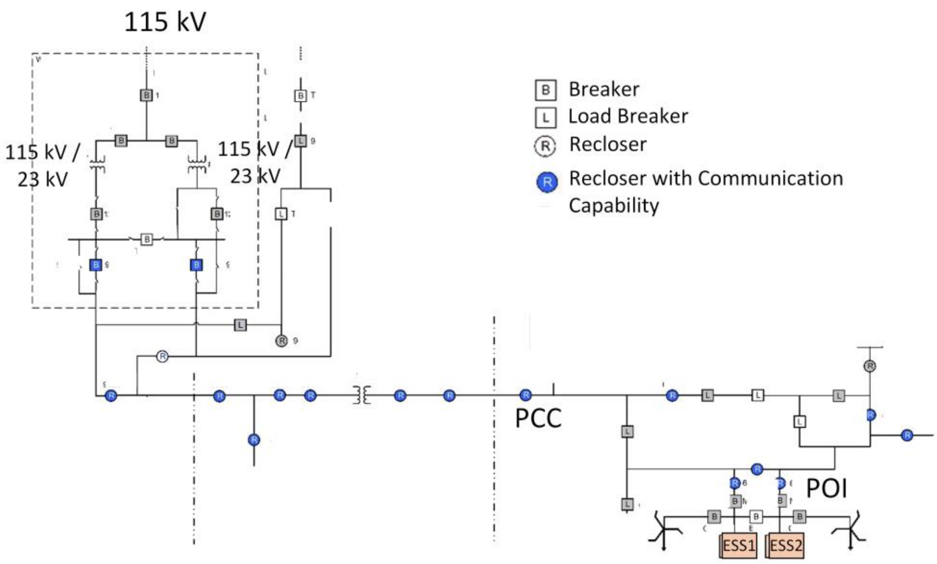

Figure 2. Sub-transmission System One Line Diagram

Figure 3. Left) Battery modules installed in battery racks, Right) Aerial view of the Provincetown BESS building

. The BESS is oversized (57.6 MVA) considering that the maximum island's load is 25 MW. Oversizing allows for detection of high impedance faults under the islanded condition by protective relays. In other words, since oversizing the BESS increases the ratio of the fault current to the normal load, it makes the protection sensitive enough to detect the smallest faults under the islanded condition. Oversizing the BESS was necessary since the BESS is the primary resource in the microgrid. There is small amount of distributed energy resources (DER) connected to the sub-transmission circuit that can provide short circuit contribution. Hence, the DERs fault contribution is not significant.

2.1. Grid-forming Inverter

A GFM inverter operates as a voltage source by creating its own voltage and frequency reference. However, the static voltage control is not sufficient for the stable operation and the automatic load sharing with other inverters and synchronous machines. There are various types of control schemes for GFM inverters, e.g., virtual synchronous machine, virtual oscillator, frequency droop and angle droop [2,4]. There are also various implementations for some of these categories. Despite the differences in implementation and control schemes, the small signal behavior of GFM inverters close to the nominal condition, i.e., in small signal, is similar [3]. However, there are distinctions among different control schemes regarding the response to large disturbances [1].

The project's GFM inverter uses the frequency droop control scheme [8]. A frequency droop GFM inverter links the load/generation imbalance and frequency deviation [3]. The frequency droop characteristics results in system-wide synchronization among synchronous machines and GFM inverters, i.e., all units reach the same frequency [1]. Similarly, the project's parallel power conversion systems maintain synchronism through the frequency droop control characteristics.

When a fault occurs, the inverter uses a FRT strategy called the virtual impedance mode to limit its output current [5]. Note that a GFM inverter behaves as a voltage source. Therefore, without a fault current limiting strategy the inverter could inject very high fault current for a nearby fault. That could in turn damage power electronics components. To help with the detection of unbalanced faults, the inverter is capable of injecting negative sequence current up to 10% of its nominal current.

2.2. BESS Operation

The project is designed to provide voltage support and peak load shaving functionality under normal and grid-connected modes and form an island in the event of a distribution fault or the loss of the transmission supply.

Several reclosers with communication capability are installed on the 23 kV circuit to which the BESS is connected. The reclosers communicate with each other to locate faults on the circuit. The information is then used to isolate the smallest part of the circuit needed for fault clearance. If there is a fault on the 23 kV circuit between the station and the point of common coupling (PCC), the BESS will pick up almost half of the circuit load seamlessly. Then, it will restore from the PCC to the recloser closest to the fault location. Based on the identified system conditions, the algorithm can reconfigure the microgrid automatically to minimize the load loss on the 23kV distribution system. The BESS controller, the microgrid and distribution automation controllers, the relays and recloser controllers will work collectively to achieve the desired mode of operation. The protective devices have different settings for grid-connected and islanded conditions.

2.3. Simulations and RTDS Testing

Steady State, transient stability, electromagnetic transient (EMT) and real-time analysis in RSCAD using the Real Time Digital Simulator (RTDS) was performed for the project.

Hardware-in-the-loop testing using the RTDS verified the desired operation of relays, the distribution automation controller, and the BESS management system.

3. FAULT RIDE THROUGH PERFORMANCE OF THE BESS

An EMT analysis was performed to evaluate the FRT performance of the BESS under different operation modes, fault types and system configurations. Transient stability tools have limitations for weak grid stability studies. Fast control loops, which cannot be represented in transient stability tools, can have a significant impact on the system dynamics under weak grid conditions. Lack of detailed converter electrical representation, inability to represent unbalanced conditions accurately are other limitations of the transient stability tools for weak grid studies [9]. Hence, an EMT analysis is necessary in this case.

The BESS performance for various transmission disturbances tested including balanced, unbalanced, N-1 and N-1-1 faults was acceptable. One observation about transmission faults was that due to the large electrical distance between the BESS POI and the transmission system, the BESS does not enter the virtual impedance mode for a fault on the transmission system, i.e., it sees the fault like a load change. Note that the virtual impedance mode is triggered by the increase in the inverter output current. For a remote fault, the inverter should have the capability to ride through the fault while operating in the normal grid-forming mode.

In contrast, control instability was observed when testing the BESS FRT performance for distribution disturbances. Control system parameter tuning was necessary to ensure stability. Slowing down the inverter response to voltage and frequency deviations resulted in significant improvement in control stability. Distribution fault clearing can take several seconds. Particularly, a lateral fault clearing time can be significantly longer than the clearing time of a fault on the backbone. The BESS is expected to ride through long distribution circuit faults. Testing various fault types at different locations is necessary to reveal potential issues.

3.1. EMT Simulation Setup

Figure 4 shows the picture of the PSCAD model used in the EMT study. The sub-transmission system modeling is very detailed including modeling of three-phase and single-phase lateral circuits, capacitor banks and voltage regulators. The area transmission system was also modeled.

The BESS model was provided and validated by the original equipment manufacturer (OEM) and it uses the actual firmware control code. Hence, it is expected that the EMT model of the BESS represents the inverter control system very closely. Sixteen power conversion systems were modeled in two blocks each including 8 inverters.

There is small amount of behind-the-meter solar PV connected to the sub-transmission system. It is not practical to model behind-the-meter resources in detail in EMT simulations due to the lack of OEM model availability and computational issues. However, since the DER amount is not significant (about 1 MW), it is not expected that those resources impact the system transients.

The BESS is the only inverter-based resource modeled in the case and it determines the system dynamics in the area after a disturbance. It is expected that a similar situation holds in practice since the BESS is the only major resource in the area with a fairly large electrical distance to the rest of the system.

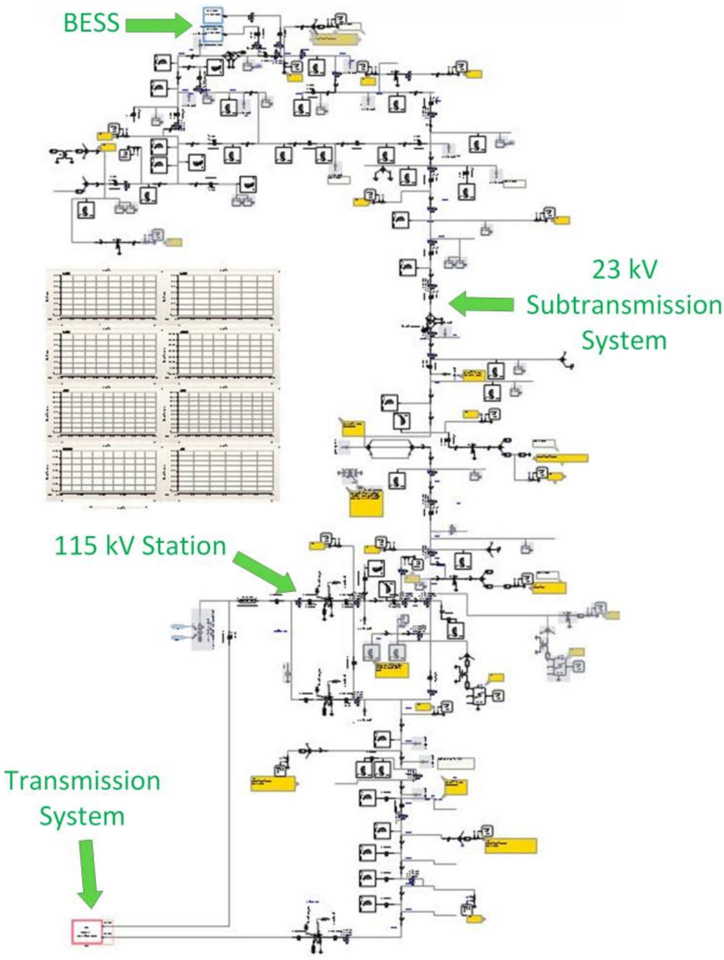

Figure 4. Study Area EMT Model

3.2. Active Power Frequency Droop Setting

Under weak grid conditions, fast inverter control response could result in instability. Our analysis shows that lowering the frequency droop setting of the GFM inverter improves the FRT performance as well as the voltage profile during a fault. The frequency droop setting changes the inverter frequency in response to change in the active power output.

Figure 5 shows the voltage along the 23 kV circuit and the inverter output for a Line to Line (LL) lateral fault with the frequency droop setting of -1 Hz/pu. Although the BESS rides through this fault and the inverter control is stable, the inverter active and reactive power output oscillations cause voltage oscillations along the circuit. The oscillations are due to excessive power transfer on the un-faulted phase, which results in power and frequency drifting based on the difference between the reference angle of the BESS and the grid angle during extended faults. Considering the long clearing time, voltage oscillations are not desirable.

Reducing the frequency droop setting slows down the change in the inverter output power by slowing down the change in the inverter frequency. As a result, it prevents the voltage oscillations in this case. Figure 6 shows the voltage along the 23 kV circuit and the inverter output for the same fault as above when the frequency droop setting was reduced from -1 Hz/pu to -0.25 Hz/pu.

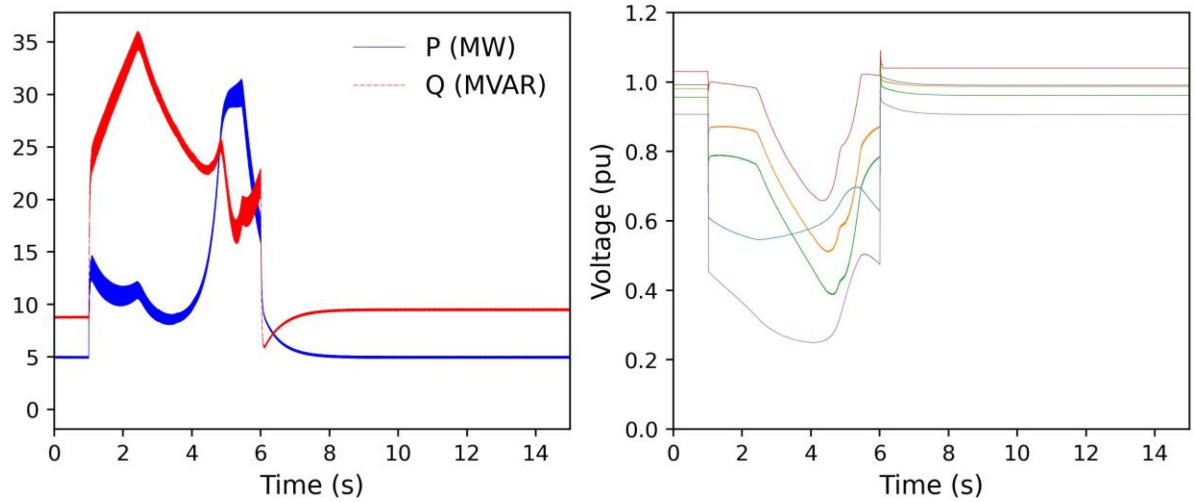

Figure 5. Left) Inverter active and reactive power output, Right) Voltage along the 23 kV circuit for a LL fault on a lateral (f_droop = -1 Hz/pu)

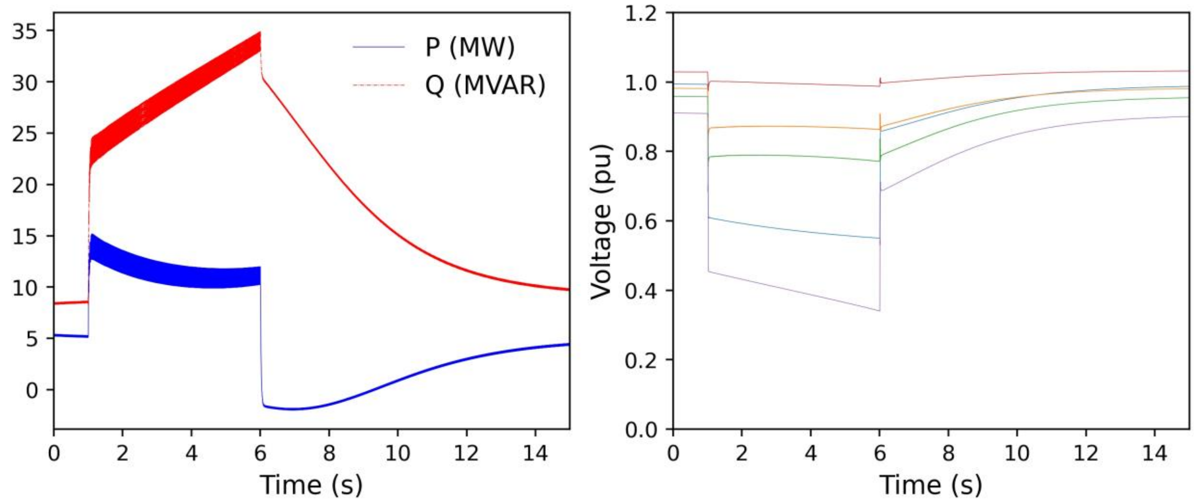

Figure 6. Left) Inverter active and reactive power output, Right) Voltage along the 23 kV circuit for a LL fault on a lateral (f_droop = -0.25 Hz/pu)

3.3. Reactive Power Voltage Droop Setting

Reducing the voltage droop setting leads to a slower rate of change of the inverter's terminal voltage in response to a change in the reactive power output, which results in a stabilizing effect on the inverter control. Considering that the BESS is connected to an ultra-weak system, the slower response of the inverter control can improve its stability. Figure 7 shows the inverter active and reactive power output and the voltage along the 23 kV circuit for a 3-phase fault on a lateral in the islanded mode with the voltage droop setting of 5% of the nominal voltage at the rated reactive power output. Figure 8 shows the inverter power output and the system voltage for the same fault after reducing the voltage droop setting to 1.5% of the nominal voltage at the rated reactive power. As the figures show, the inverter control is unstable with the droop setting of 5% while it maintains stability with the lower droop setting. Investigating the reason for instability shows that it is due to the fast response of the inverter control system under the weak grid condition. Any control interaction between the project and other resources, e.g., synchronous machines, was not identified.

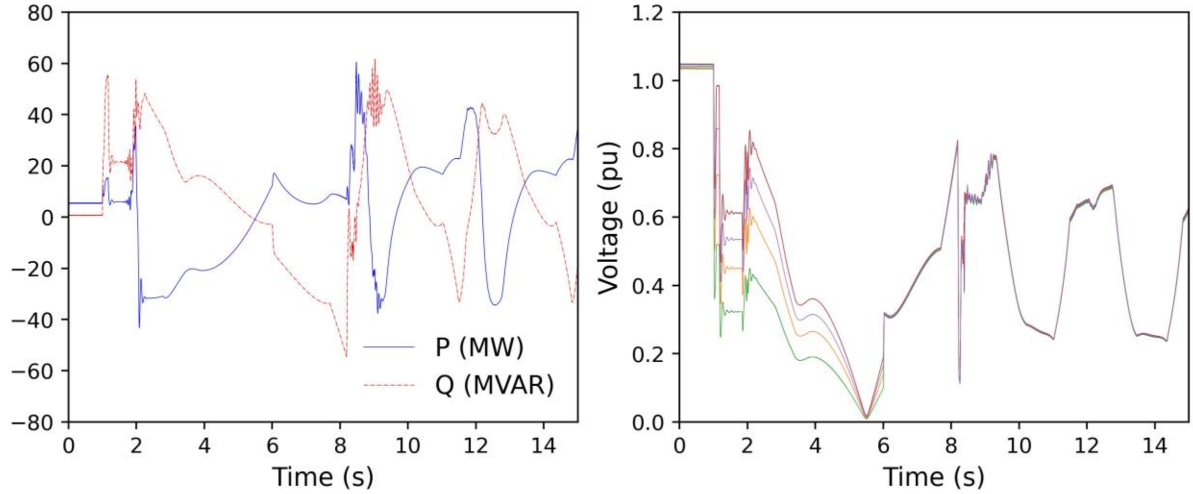

Figure 7. Left) Inverter active and reactive power output, Right) Voltage along the 23 kV circuit for a LLL fault on a lateral (V_droop = -0.05)

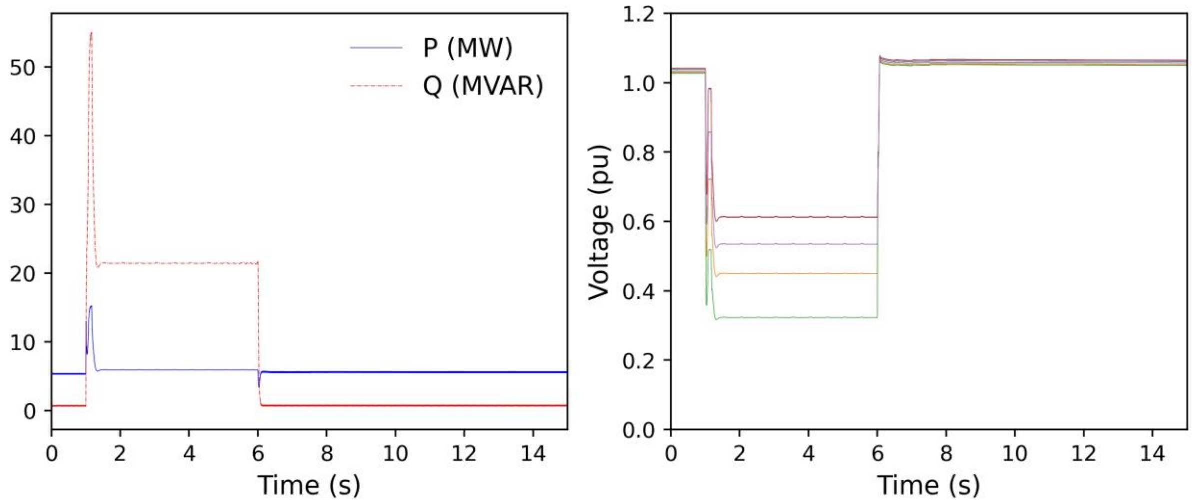

Figure 8. Left) Inverter active and reactive power output, Right) Voltage along the 23 kV circuit for a LLL fault on a lateral (V_droop = -0.015)

3.4. Fault Ride Through Cycling

Unlike GFL inverters that typically enter the FRT mode based on their terminal voltage, the project's GFM inverter enters the FRT mode based on a current threshold. Once the inverter enters the FRT mode, if the terminal voltage reaches a certain level the FRT mode will be deactivated.

Setting appropriate values for the FRT current and voltage thresholds is necessary to prevent the inverter control from cycling between the FRT mode and the normal operating condition as cycling between operation modes is not desirable and can potentially result in control instability. This is challenging in a weak system as the injection of a small amount of reactive power could result in significant voltage rise. However, increasing the FRT current threshold helps the inverter not to enter the FRT mode for a shallow fault, i.e., far from the POI. Reducing the reactive current injection during the fault is another strategy to mitigate or prevent the FRT cycling.

Figure 9 shows the inverter output and the voltage on the 23 kV sub-transmission system for a LL lateral fault when the FRT current threshold was set to 0.8 pu. Once the inverter enters the FRT mode, its reactive current injection results in significant voltage rise. As a result, the FRT mode is deactivated. However, since the fault is not cleared yet the inverter output current increases again and the FRT mode is reactivated. This results in cycling between the normal operation and the FRT mode. The inverter abnormal voltage protection does not trip the inverter in this scenario since the inverter terminal voltage is not high or low for long enough to trigger the protection action.

Increasing the FRT current threshold resolved the FRT cycling. Figure 10 shows the inverter output and the voltage on the 23 kV sub-transmission system for the same fault as in Figure 9 with the FRT current threshold set to 1.2 pu.

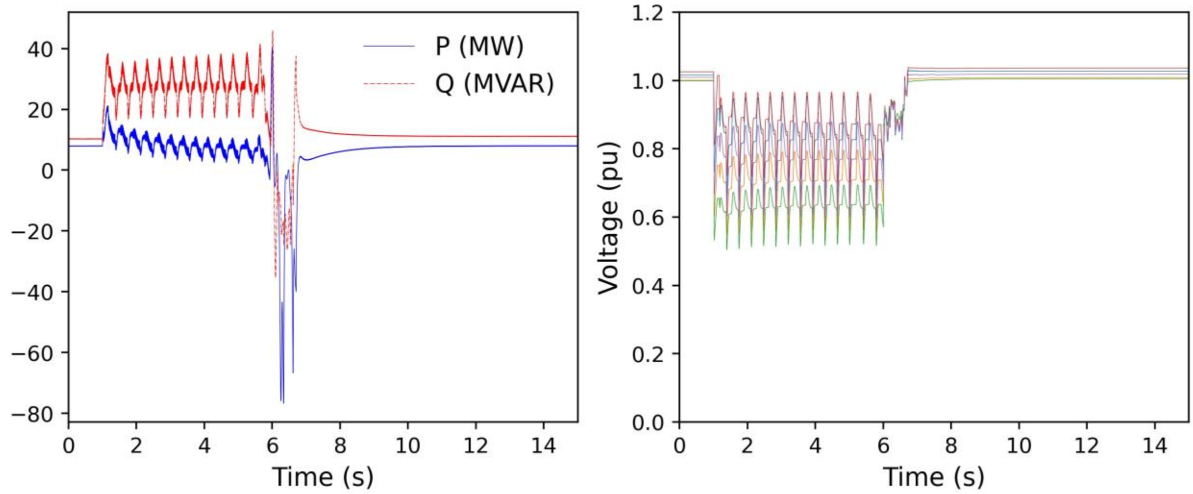

Figure 9. Left) Inverter active and reactive power output, Right) Voltage along the 23 kV circuit for a LL fault on a lateral (FRT Current Threshold = 0.8 pu)

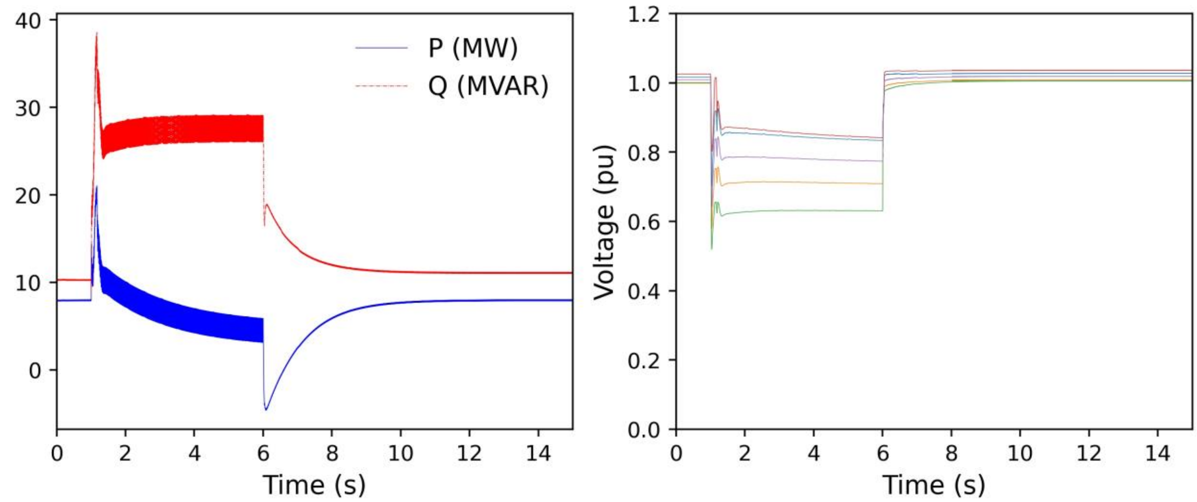

Figure 10. Left) Inverter active and reactive power output, Right) Voltage along the 23 kV circuit for a LL fault on a lateral (FRT Current Threshold = 1.2 pu)

4. BESS OPERATION

The project was placed in-service in Spring 2022. Figure 11 shows the measurements of the BESS output during an islanding test performed as part of the project's commissioning. The BESS was in the standby mode prior to opening of the PCC breaker, i.e., it was regulating its terminal voltage without injecting or absorbing any active power. Once the breaker was opened, the BESS active power output matched the island load seamlessly. This test confirms that the BESS is capable of seamless transition from the grid-connected mode to the islanded mode due to the voltage source behavior of the GFM inverter.

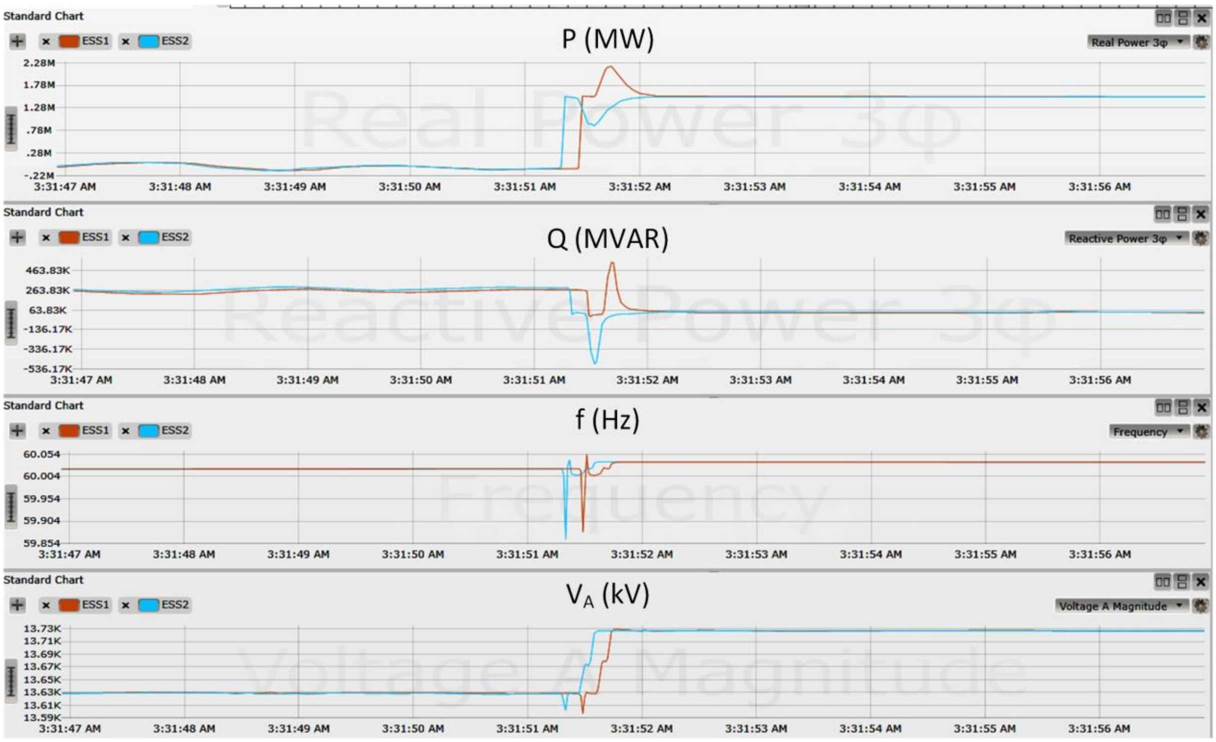

Figure 11. BESS output measurements from the islanding test

5. CONCLUSIONS AND FUTURE WORK

The Provincetown BESS project intended to improve the Eversource's distribution system reliability showcases the capability of the grid-forming inverter technology to operate reliably under an ultra-weak grid condition and transition seamlessly from the grid-connected mode to the islanded operation. However, the EMT analysis results show that grid-forming inverters are prone to control instability under weak grid conditions. Hence, control system parameter tuning may be necessary to ensure stability. Our comprehensive analysis shows that testing a variety of disturbances under different configurations and operation modes could reveal potential stability issues and the results were informative for proper inverter control parameter tuning. Future work will focus on analyzing the operating measurements of the BESS performance under different configurations and disturbances and comparing the operational data with simulation results.

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