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Real-Time Simulation of Microgrid Protection Schemes under Dominion Energy's Locks Microgrid

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SUMMARY

Virginia's Grid Transformation & Security Act of 2018 encouraged utilities in Virginia to increase the capacity of renewable resources on the electrical grid, enhance the grid's resiliency and security, and ensure service for customers. In response, Dominion Energy Virginia is expanding Locks Campus and creating a microgrid, where it will be able to conduct comprehensive research into the interactions between the microgrid and the main grid. The distributed energy resources in the Locks Microgrid are mainly inverter-based resources. However, the inverter-based resources used in today's microgrids do not behave like traditional synchronous generators. They have lower inertia, faster responses, and smaller fault current. This complicates protection schemes between the main grid and a microgrid. For example, to avoid over-tripping, relay coordination is needed between the recloser at the microgrid's point of interconnect and the substation feeder circuit breaker. Dominion is currently using its real-time digital simulator to create a realistic environment for modeling and testing. For this project, the Locks Campus Microgrid was modeled in RSCAD, and three protection scenarios were tested using real-time simulation. The simulation results demonstrate that coordinated relays can respond to faults at different locations, and the microgrid can operate in islanded mode.

KEYWORDS

Microgrid, Resilience, Real-time simulation, RTDS, Microgrid protection

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I. Introduction

Over the decades, microgrids have been deployed to enhance system resiliency and to serve loads independently. The Department of Energy defines a microgrid as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and islanded mode" [1]. A microgrid is designed to enhance system resiliency [2] due to its capability to withstand and recover from disruptions and operate independently. Because of their versatility, microgrids will be a valuable tool in designing a carbon-neutral grid of the future.

In response to Virginia's Grid Transformation & Security Act of 2018, Dominion Energy has studied microgrids extensively [3] over the last few years and has extended its research in microgrid protection. Dominion is currently building a Technical Support Building (TSB) and distributed energy resources (DERs) within the Locks Campus which will provide a living laboratory for microgrid research.

Incorporating a microgrid into the synchronous distribution system presents challenges to the existing protection system. These protection schemes were designed with radial topologies, and they assume a one-way flow of power. With a microgrid, however, the distribution system's power flow can become bi-directional, which complicates the design of protection systems. Another challenge is that the inverter controller has a current threshold which, when surpassed, suppresses output current. If a fault occurs on the distribution line, an improperly designed microgrid would not be able to detect it.

To ensure proper relay operation and verify microgrid control algorithms, accurate system modelling and simulation are essential. A real-time digital simulator (RTDS) is a suitable tool for relay testing, since it uses parallel processing to represent a power system in real time. This real-time simulation capability then allows hardware-in-the loop (HIL) simulation to evaluate hardware performance. This process has been widely used in hardware design validation. In [4] and [5], a microgrid controller and a microgrid management system were implemented and tested using HIL simulation. The behaviors of the inverter and phasor measurement units were also verified in [6] and [7]. Impedance distance relays were tested as part of Dominion Energy's Blackstart plan [8]. Dominion plans to install a recloser relay at the point of interconnection (POI) on the Locks Microgrid. HIL testing for these devices will be conducted before construction.

This paper reviews a preliminary simulation focusing on control algorithms and protection schemes for inverter-based resources (IBRs); the simulation can later be used for HIL testing. To enable the grid-connected and islanded microgrid operations, inverter-based resources must be able to work in both grid-following and grid-forming modes [9]. Grid-following IBRs dispatch power flow from the microgrid while the main grid is connected. Grid-forming IBRs maintains system voltage and frequency when the main grid is disconnected and the microgrid is islanded.

This paper is organized as follows. Section II describes the Locks Microgrid system. Section III presents the protection schemes studied. RTDS simulation results are discussed in Section IV. The conclusion and suggestions for future work are given in Section V.

II. Locks Campus Microgrid

Dominion Energy Virginia is in the process of installing a microgrid at its Locks Campus near Dinwiddie, VA in order to better understand the behavior of microgrids. With the real-word data it collects, Dominion will be able to study the performance of distributed energy resources (DERs) under grid-connected and islanded modes, the integration of renewable resources, the control algorithm of IBRs, and microgrid protection schemes. Building this test bed will function as a steppingstone as Dominion transitions towards a carbon neutral future.

The Locks Microgrid will be connected to a 34.5 kV distribution system and will operate by using one battery energy storage system (BESS) and five photovoltaic (PV) systems to serve the campus load (see Fig. 1). The ratings of the DERs and loads are found in Table I, which shows a total of 2116 kW energy resources, and Table II, which shows a total of 286 kW load demand. The Locks Microgrid was modeled in RSCAD with a recloser at the POI. An equivalent voltage and 0.5 MW lumped load were added to represent the grid and demand of the distribution system.

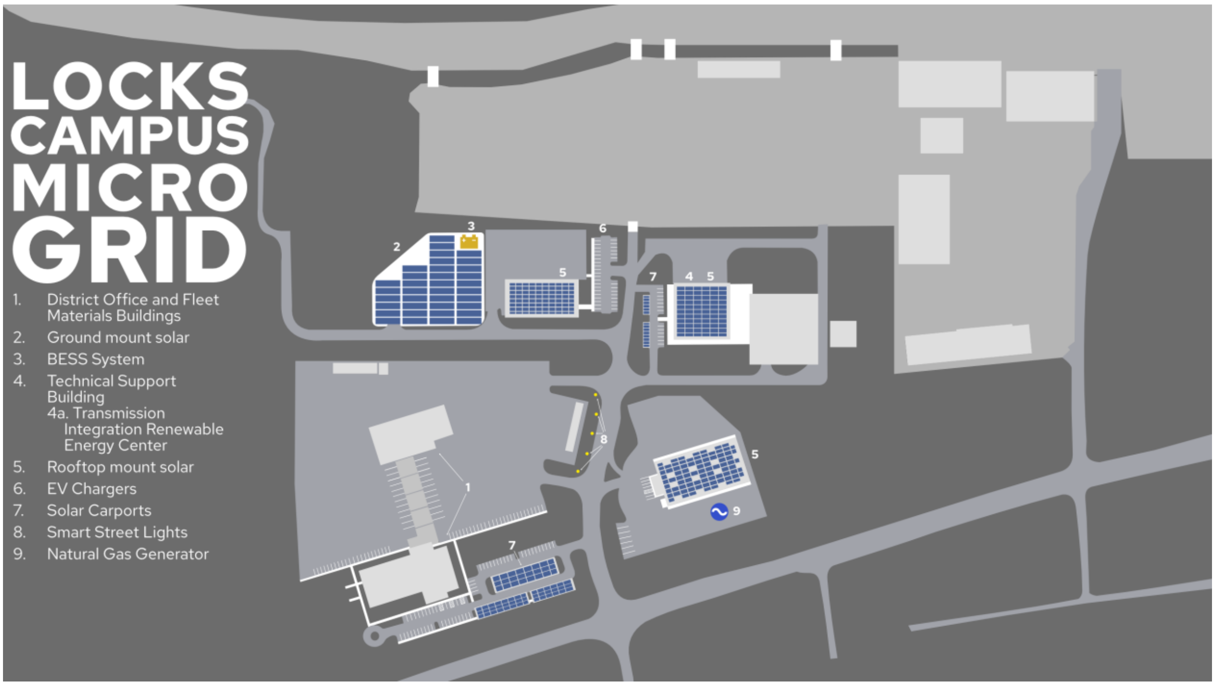


Fig. 1. Dominion Energy Locks Campus

Table I. Ratings of DERs in Locks Microgrid

DERs	Location	Rating
BESS	3. BESS system	1 MW / 4 MWh
Solar1	5. Rooftop Mount Solar	180 kW
Solar2	5. Rooftop Mount Solar	96 kW
Solar3	2. Ground Mount Solar	400 kW
Solar4	5. Rooftop Mount Solar at 3.	240 kW
Solar5	7. Solar Carports	200 kW
Total		**2116 kW**

Table II. Load Demands in Locks Microgrid

Loadings	Location	Demand
Load1	1. Fleet Materials building	64 kW
Load2	1. District Office	98 kW
Load3	Additional Buildings	124kW
Total		**286 kW**

When the microgrid is connected to the main grid, the PV system and the BESS will operate seamlessly as part of the grid. The PV inverter will be set to grid-following mode and will control its output power using maximum power point tracking (MPPT). The BESS inverter will control power dispatch based on its power quality (PQ) setting.

When the main grid is lost, the BESS will switch to grid-forming mode, becoming its own grid, or island, that will independently establish the microgrid voltage, frequency, and V/F control.

III. Microgrid Protection Schemes

One of the constraints on the microgrid is the number of building loads that can be supported by the BESS system in islanded mode. Several of the buildings included in the microgrid island were chosen due to their load profiles, while several others had to be omitted because of their size. Because the campus is being partitioned, the protection and control schemes need to isolate the buildings specifically supported by the BESS. The schemes also must initiate the start of a backup generator to support the buildings which will not be supported by the BESS.

This project demonstrated three scenarios which are described in more detail below. They include two fault events and a demonstration of load shedding during islanding.

Scenario 1:
When a fault occurs inside the Locks Microgrid, the fault current will flow from the substation into the microgrid. Overcurrent protection will detect the fault current and trip the recloser. Since the circuit breaker and recloser are coordinated, the fault will be isolated by the recloser without tripping the circuit breaker. Fig. 2 shows the flow chart of this scenario.

When the fault is cleared and the recloser closes, the load demands in the microgrid will be picked up. Then the BESS and PV systems will restart in grid-following mode.

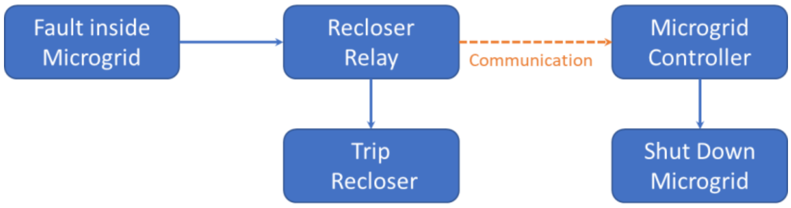


Fig. 2. Protection Scheme for Fault Inside Microgrid

Scenario 2:

When a fault occurs outside of the microgrid on the distribution line, the IBRs may not be able to contribute enough fault current to trip the recloser. In that case, the fault current from the substation will trip the circuit breaker. That will send a transfer trip to the recloser and isolate the microgrid from the fault. Since the fault is located on the distribution line, the microgrid will operate in islanding mode after the recloser is tripped. Fig. 3 shows the flow chart for this scenario.

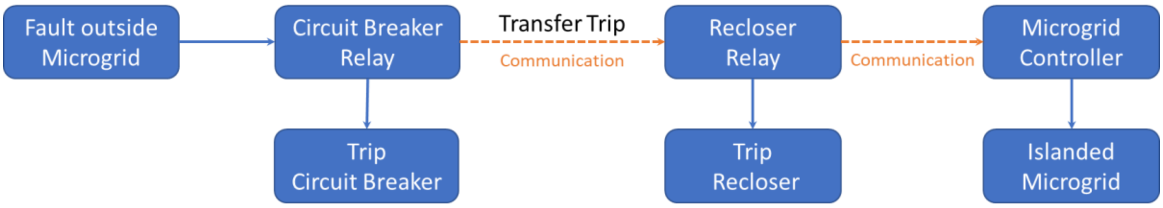


Fig. 3. Protection Scheme for Fault Outside Microgrid

Scenario 3:

To operate as an islanded microgrid, the BESS will function in grid-forming mode to establish the microgrid's voltage and frequency. The microgrid will resynchronize once the main grid becomes available. If the BESS's state of charge (SOC) drops below 40%, load will be shed. Before the recloser can be closed, the voltage, frequency, and phase angle need to be within the tolerances specified in IEEE 1547-2018 [10]. Once the fault is cleared, the circuit breaker will close to energize the distribution system. Then the synchronization process will be executed to reconnect the microgrid to the main grid. Fig. 4 shows the flow chart of this scenario.

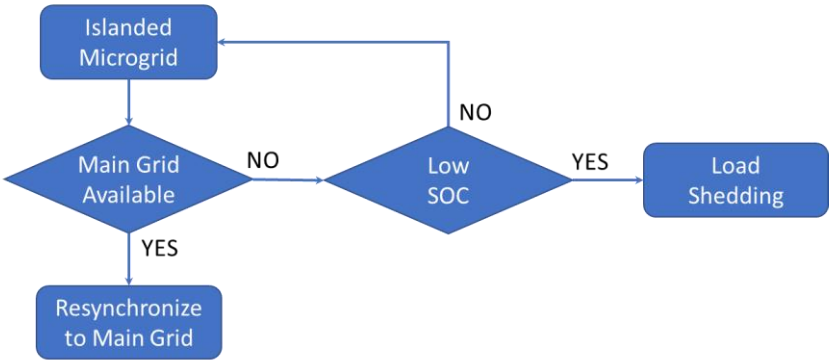


Fig. 4. Islanded Microgrid Resynchronization and Load Shedding

IV. Simulation Results

A real-time simulation was implemented in RTDS using these three scenarios to predict the performance of the Locks Microgrid.

Initial Condition:
Under the initial condition in the grid-connected simulation, all PV systems worked on MPPT, and the BESS worked on PQ control. Since the solar output in the Locks Microgrid was expected to be larger than the load demand, the BESS was set to absorb solar power and use it to recharge.

Fig. 5 illustrates the power flow through the POI and the output power of the DERs. The power provided from the substation was about 0.52 MW, and 0.02 MW was injected into microgrid through the POI. The combined generation of the main grid and PV systems was 1.6 MW. The total load was 1.486 MW and the BESS absorbed 0.1 MW, for 1.586 MW total demand. The total output power of the PV systems was 1.58 MW.

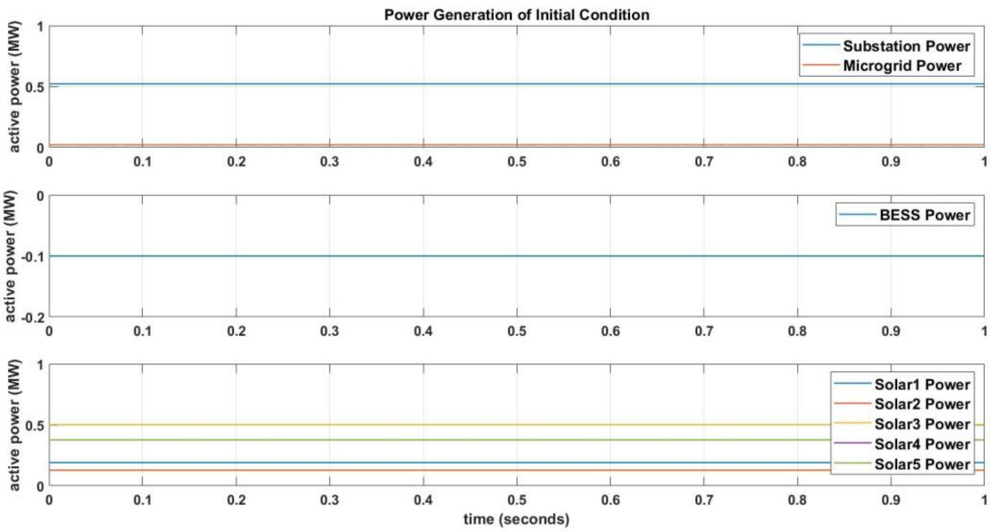


Fig. 5. Power Generation of Initial Condition

Scenario 1:
In Scenario 1, a three-phase ground fault was applied inside the Locks Microgrid at 0.1 seconds. Since the recloser was tripped by the overcurrent relay, the microgrid controller was able to identify that the fault was inside the microgrid and shut down the DERs in 100 milliseconds.

Fig. 6 shows the fault current through the circuit breaker and recloser. Since the fault was inside the microgrid, both the circuit breaker and recloser saw the fault current at around 2000 A, which tripped the recloser in 0.2 seconds (12 cycles).

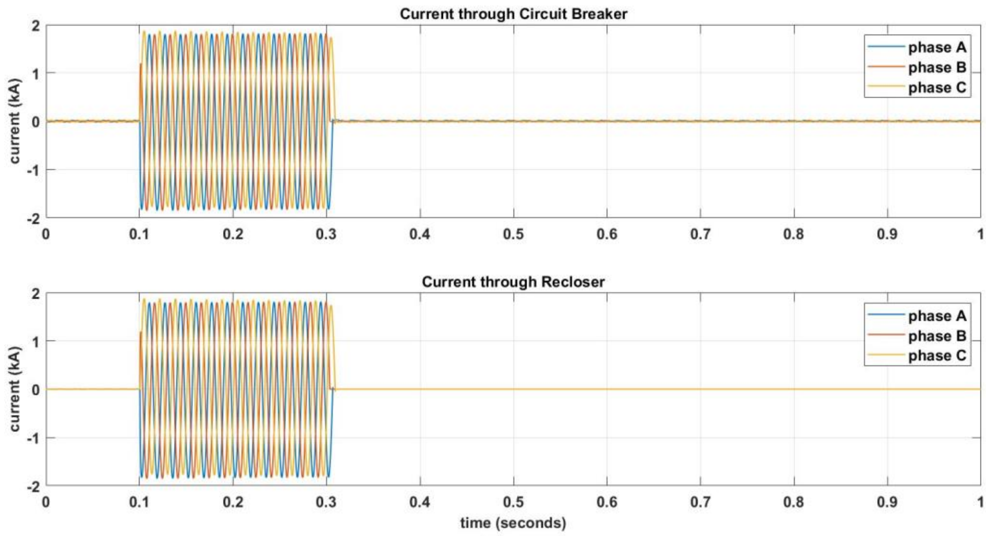


Fig. 6. Fault Currents in Scenario 1

Fig. 7 shows the status of the breaker and switches. When the fault occurred, the recloser and TSB tripped in 0.2 seconds. Then after the recloser tripped, the microgrid controller disconnected the BESS and PV systems in 100 milliseconds.

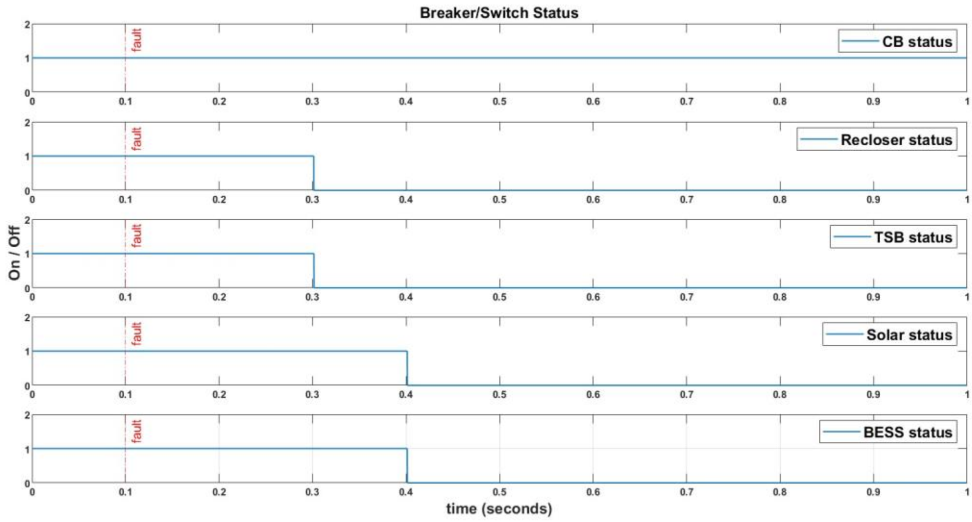


Fig. 7. Breaker/Switch Status in Scenario 1

Fig. 8 shows the voltages at the POI. On the grid side, the voltage dropped during the fault and recovered after the fault was isolated by the recloser. On the microgrid side, the voltage dropped to zero after the microgrid controller disconnected the DERs.

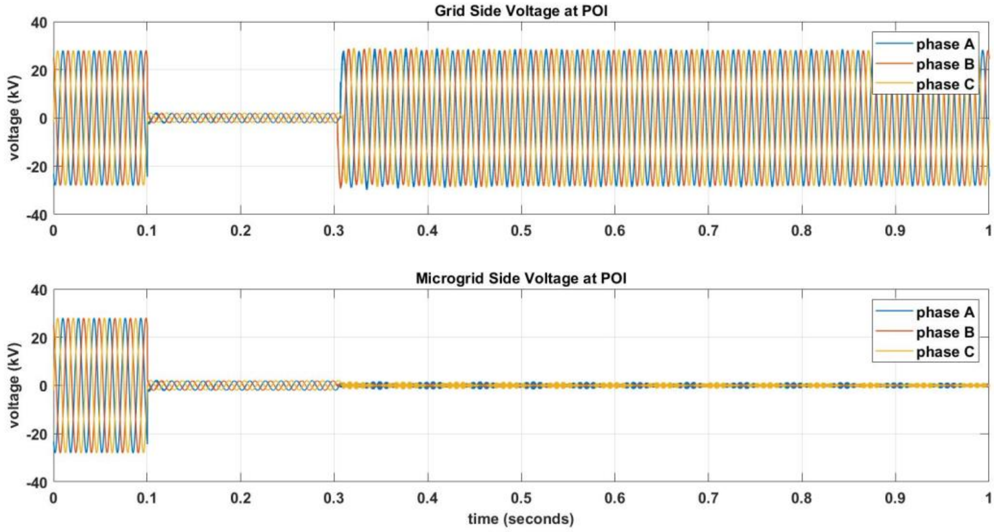


Fig. 8. POI Voltages in Scenario 1

Scenario 2:

In Scenario 2, a three-phase ground fault was applied outside the Locks Microgrid at 0.1 seconds. Since the inverter controller suppressed the output current, the fault current through the recloser was not enough to trip it. The circuit breaker relay tripped in 0.6 seconds (36 cycles), and a transfer trip was sent to the recloser relay after a 100-millisecond communication delay. Fig. 9 shows the fault currents through the circuit breaker and recloser. The fault current was less than 300 A through the recloser, and more than 2000 A through the circuit breaker.

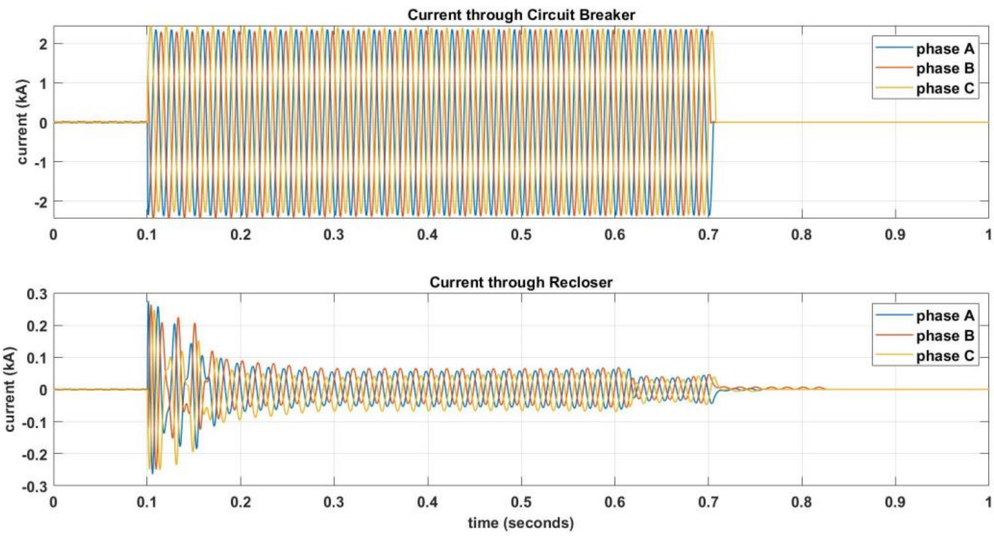


Fig. 9. Fault Currents in Scenario 2

Fig. 10 shows the status of the breaker and switches. The fault was applied at 0.1 seconds and the circuit breaker tripped 0.6 seconds later. The transfer trip signal tripped both the recloser and the Technical Building's circuit breaker in 100 milliseconds. In this case, the microgrid controller switched the BESS to grid-forming mode and restarted the microgrid. Once the recloser was opened, the PV systems were disconnected in 100 milliseconds. The BESS control mode then switched on in another 100 milliseconds.

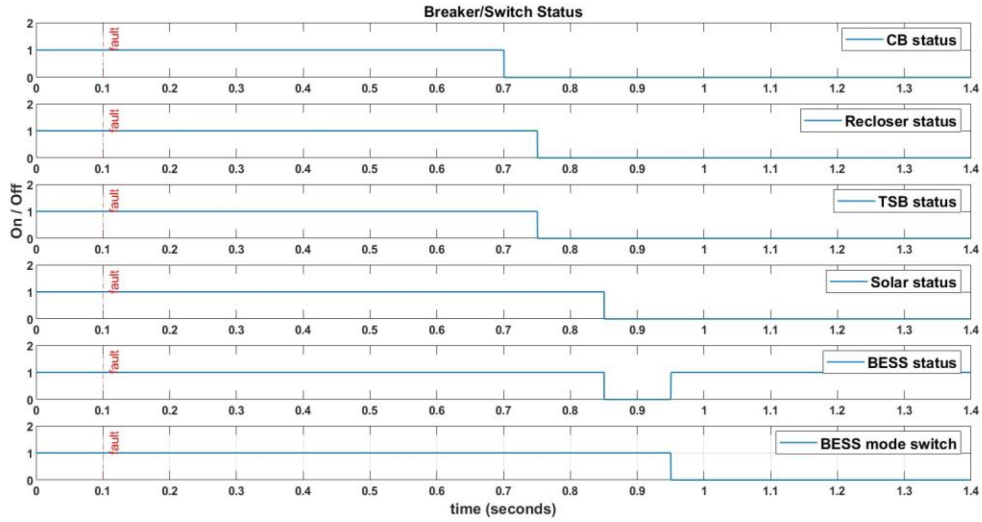


Fig. 10. Breaker/Switch Status in Scenario 2

Fig. 11 shows the voltages at the POI. On the grid side, the voltage dropped during the fault event and went down to zero after the circuit breaker tripped. On the microgrid side, the voltage recovered after the BESS restarted under grid-forming mode. Based on the PV inverter installed, after a disturbance a 0.9 p.u. microgrid voltage is required within 2 seconds to prevent the inverter from shutting down. Fig. 12 calculates the microgrid's three-phase RMS value in per unit. The results indicate that the voltage came back in less than two seconds.

Fig. 11. POI Voltages in Scenario 2

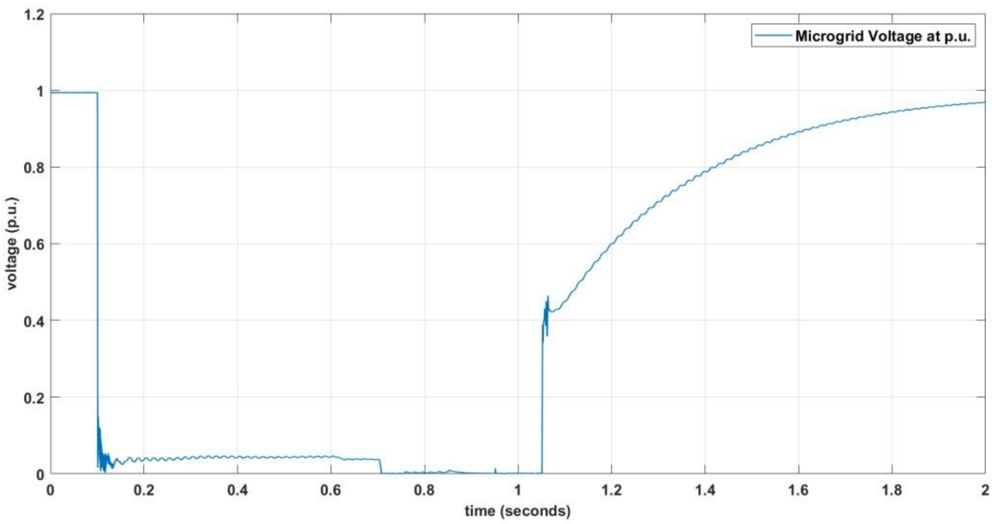


Fig. 12. Microgrid Voltages in p.u. in Scenario 2

Fig. 13 illustrates the output power of the BESS when it picked up the loads under islanded mode. Since the Technical Support Building tripped and was served by its backup generator, the total loading was 286 kW for the rest of the substation. In this simulation, the output power of the BESS rose from absorbing 0.1 MW pre-fault to providing approximate 0.3 MW post-fault.

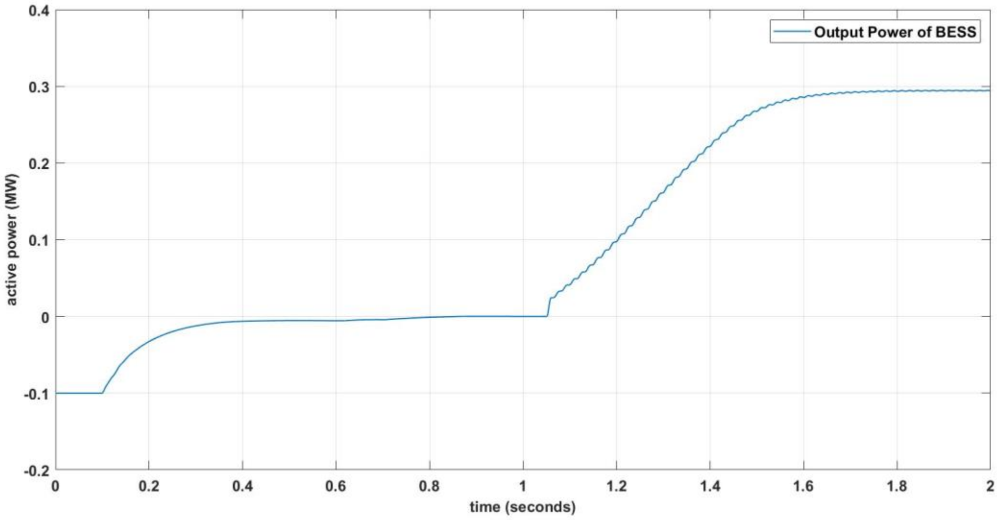


Fig. 13. BESS Output Power in Scenario 2

Scenario 3:

In Scenario 3, the Locks Microgrid was islanded following the fault in Scenario 2. If the fault cleared, the microgrid would resynchronize and connect to the main grid. If the fault was unable to be cleared on time, the BESS would discharge for minutes to hours. Then the load shedding scheme would be initiated to serve the critical loads longer.

Fig. 14 illustrates the measurements of the synchroscope, which identifies the instant two systems are synchronized. Located at the POI recloser, the synchroscope measures the voltage and frequency of both sides. According to IEEE 1547-2018, the voltage difference must be within 1%, the frequency difference within 1 Hz, and the angle difference within 15 degrees.

Before resynchronization, the voltage magnitude of the microgrid side was almost identical to the main grid side when using the voltage control capacity of the BESS in its grid-forming mode. The frequency of the islanded microgrid was based on the BESS's droop curve, and it operated at 59.86 Hz. The resynchronization was activated at 0.1 seconds when the angle difference was ~50 degrees, then the recloser waited until the angle difference was less than 15 degrees. After the relay closed, the voltage, frequency, and angle differences dropped to zero.

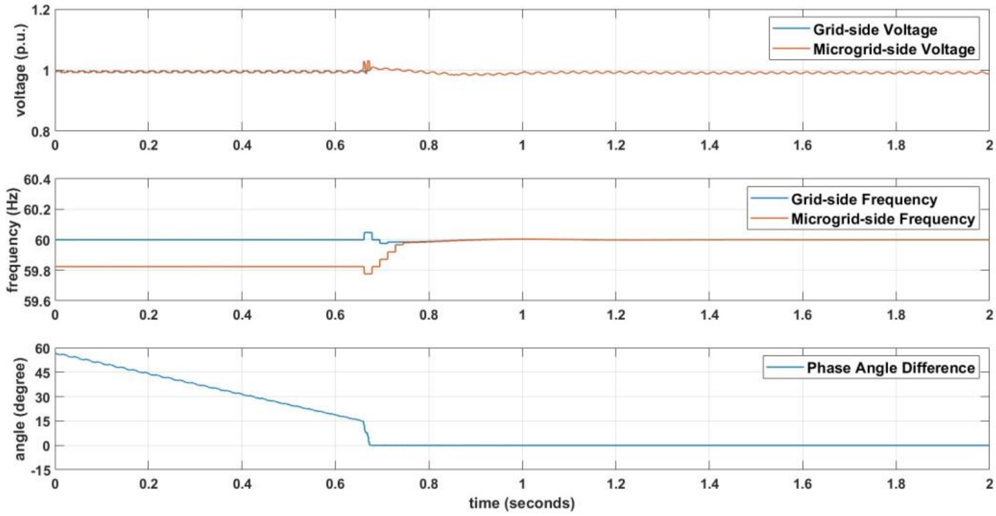


Fig. 14. Synchroscope Measurements

Fig. 15 shows how the power flowed during resynchronization. When the recloser closed, the main grid injected power into the microgrid. The power provided from the substation increased, and the power flow through the POI increased from zero. Since there was enough power injection to serve the microgrid, the BESS output power dropped.

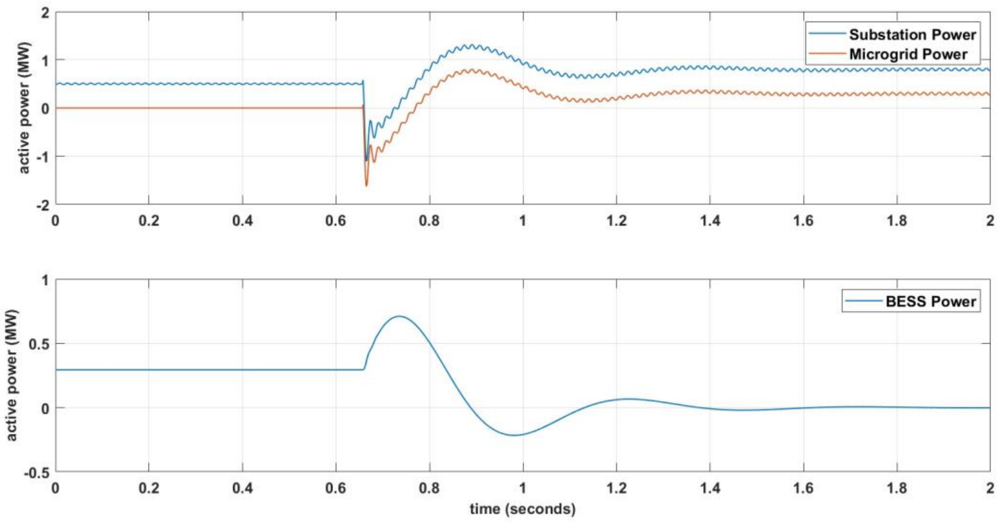


Fig. 15. Power Generation of Resynchronization

Fig. 16 demonstrates the load-shedding scheme. The load for the Fleet Materials Building (FMB) was set to be shed once the BESS's state of charge (SOC) was lower than 40%. The FMB's switch was opened at 1 second once the SOC reached 40%.

Fig. 17 shows the BESS's power change during islanded mode. Its output power decreased to ~64 kW after the load from the FMB was shed, which allowed the storage system to serve critical loads for a longer period.

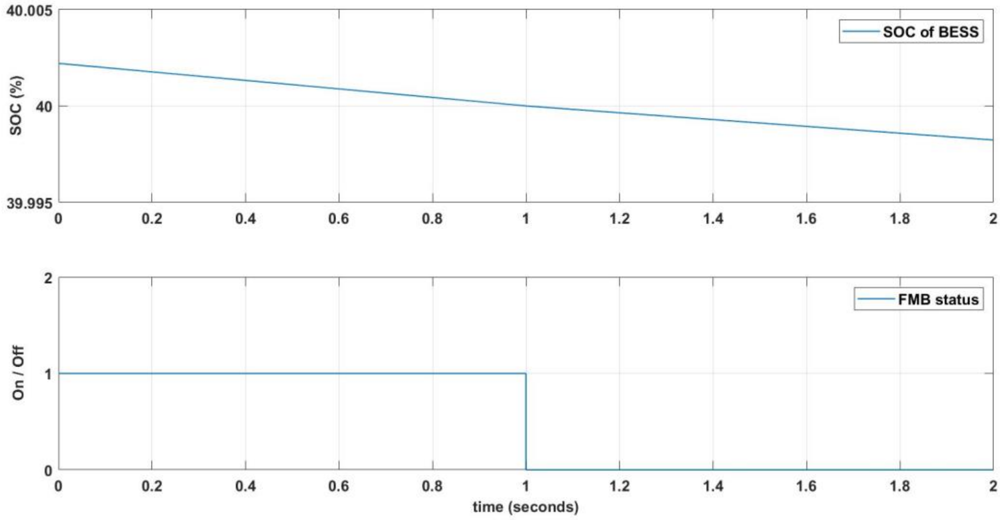
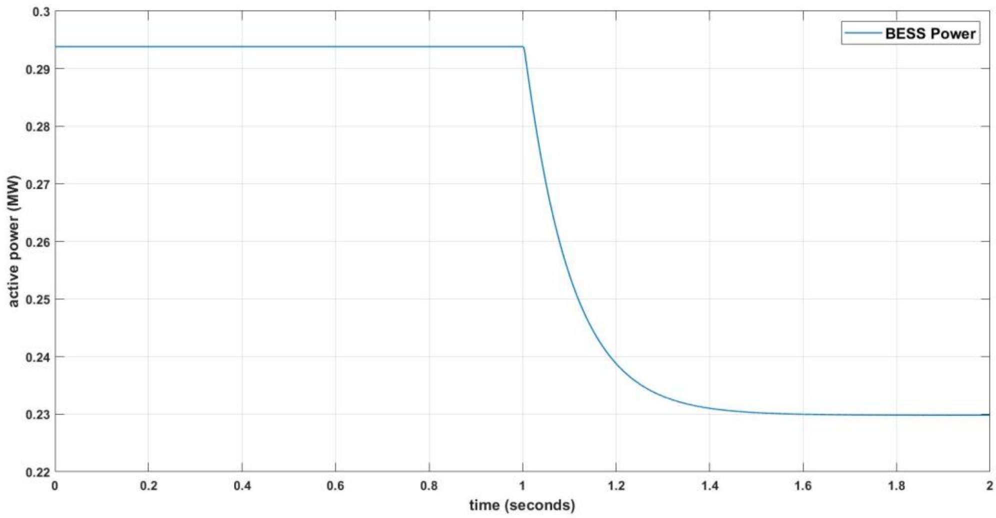


Fig. 16. Load-Shedding at the Fleet Materials Building



V. Fig. 17. Power Generation of the BESS During Load-Shedding

VI. Conclusion

The Locks Campus Microgrid was modeled in RSCAD to evaluate microgrid protection and control. Three scenarios were simulated on the RTDS platform, and the simulation results validated the proposed protection and control schemes.

When a fault occurs inside a microgrid, the protection relay should isolate the microgrid while maintaining the distribution system. But if the fault occurs outside the microgrid, a transfer trip to the recloser will be activated. The microgrid will operate under islanded mode, where the BESS discharges and the SOC decreases. Therefore, resynchronization and load-shedding schemes were simulated as well, to demonstrate either reconnection to the main grid or the reduction of output power in the BESS.

The future work for this project is to implement an HIL simulation in order to test the hardware in real time. For example, an SEL-651R recloser relay could be installed at the POI with the Locks Microgrid. The HIL simulation can be used to verify the relay's overcurrent, transfer trip, and resynchronization functions. By implementing the HIL simulation, Dominion can evaluate the relay's performance and have the opportunity to fine-tune it before operation.

VII. Acknowledgments

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