Microgrid Seamless Transitions Between Grid-Tied and Islanded Operation: A Case Study

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***Abstract*—The authors recently contributed to the successful design and commissioning of a microgrid system. This microgrid system is capable of seamlessly transitioning between grid-tied and islanded operation, both during planned operations and during unplanned system events. The experiences and lessons learned from this project are presented and extrapolated to identify characteristics of microgrids that are conducive to achieving seamless transitions within the breadth of possible system conditions.**

***Index Terms*—microgrid, seamless transition, islanded operation, resilience, protection, relaying**

I. INTRODUCTION AND SYSTEM DESCRIPTION

The authors recently supported North Bay Hydro in designing and commissioning a fully functional microgrid at the Community Energy Park (CEP) facility in North Bay, Ontario, Canada. The microgrid supplies electrical power and heat to community facilities of North Bay. These facilities include Memorial Gardens arena, YMCA/Aquatic Center, and outdoor lighting for Thomson Park sports fields. The microgrid is comprised of the following Distributed Energy Resources (DERs):

- Two Combined Heat and Power (CHP) natural gas generator systems, each rated 265 kWe
- One Battery Energy Storage System (BESS), rated 250 kW AC, 274 kWh
- Solar photovoltaic systems totaling 8 kW AC

Thus, the microgrid system supplies a maximum of 788 kW electrical power. The CHPs also produce thermal energy which is used to heat the community facilities.

A simplified single line diagram of the microgrid is provided in Fig. 1. Only one of the two Utility interconnection breakers are closed at any instance.

A. Grid-Tied Operation

Under normal conditions (when utility power is available), the CHPs are utilized to minimize the amount of power imported from the utility. The microgrid controller sends a power setpoint command to the CHPs based on the system loading conditions. Care is taken to avoid exporting power to the grid, as this is a load displacement generation. The microgrid control system targets a small amount of power import from the utility, to provide a buffer.

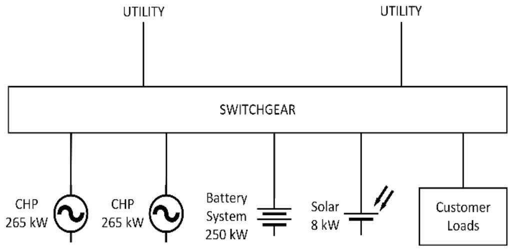

Figure 1. Community Energy Park Microgrid – Simplified Single Line Diagram

In grid-tied operation, the BESS can be used to provide reactive power support, or it can be charged in preparation for islanded operation. The BESS is also used to quickly remediate power export conditions which occur after load rejection.

B. Islanded Operation

When the microgrid system is islanded, the CHPs are operated in isochronous mode, with integral controls that manage load sharing between the two CHPs. The BESS is operated in frequency droop mode to improve system stability and reduce the effective load step on the CHPs during sudden load changes.

C. Transitions

The microgrid system is capable of automatically and seamlessly transitioning between grid-tied and islanded operation. The term "seamless transition" is defined as the connection and disconnection of a microgrid to and from the larger grid accomplished without voltage and frequency transients that exceed the specifications of the microgrid design and the interconnection requirements [1]. Transitions between grid-tied and islanded mode of operation may either be planned or unplanned. An example of a planned transition is a manually initiated return transfer from islanded to grid-tied operation. An example of an unplanned transition is an automatic transfer from grid-tied to islanded operation in response to a utility grid disturbance.

In the CEP microgrid, planned transitions are seamless, and furthermore, planned transitions are effectively unnoticeable from the perspective of loads. During unplanned seamless transitions from grid-tied to islanded operation, the power system frequency sags briefly, but a momentary outage is avoided.

The microgrid transitions presented several technical challenges. The transition sequences and control strategies had to be adapted to the system load conditions. There remain opportunities to improve the microgrid capabilities in unusual circumstances.

The sequences and control strategies for the microgrid's transitions are detailed in the following section. Then, the unique technical challenges and lessons learned are explored.

II. SEAMLESS TRANSITIONS

A. Planned Transitions from Grid-tied to Islanded Operation

There microgrid can perform a transition away from the utility and run instead on local DERs. This may occur in preparation for a known utility outage (e.g., maintenance on a distribution feeder) or in advance of a significant weather event with high likelihood of a service interruption.

The seamless transition from grid-tied to islanded operation requires a series of steps to prepare the assets before opening the interconnection breaker and then maintain grid operation while islanded. The general process is listed below.

- Confirm that all required assets are operational.
- Turn on enough DERs to supply the load or ensure that there is sufficient DER already online.
- Low priority loads may be shed if the microgrid demand exceeds the available DER capacity.
- Balance the load at the interconnection breaker, then trip the breaker.

Once islanded and isolated from the utility, additional processes execute to turn on any remaining DERs and then maintain a stable electrical grid.

The CEP operators work closely with microgrid facility management in the event of a planned transition and while the system is islanded to manage facility loads in accordance with DER capacity. This operations strategy eliminates the need for automatic load shedding, which would have been costly to implement since the existing building switchboards do not have remote control capability.

The steps for a seamless transition from grid-tied to islanded operation are detailed as follows.

1) Turning on DERs for transition

The microgrid controller calculates the total system load, a combination of present DER output and net power import across the interconnection breaker. Sufficient DERs are brought online to satisfy this demand, with an additional safety margin. DERs are prioritized based on device availability and operator preference.

2) Minimize power flow at interconnection breaker

Once DERs online have sufficient capacity, the microgrid controller sends power commands to each DER to adjust the output to minimize the power flow across the interconnection breaker. Normal load variations cause some power flow across the interconnection breaker. Once the power measurement falls within a defined low-power range, a trip command is sent to the interconnection breaker and the island is formed.

3) DER control mode adapts to support islanded operation

As soon as the CHP controls detect that the interconnection breaker is open (based on a breaker status contact), the CHPs automatically switch from base-load (grid-following) to isochronous (grid-forming) mode to support islanded operation.

B. Planned Transitions from Islanded to Grid-tied Operation

While operating in island mode, the system can perform a seamless transition back to a stable utility. This operation can happen automatically (after a specified delay upon seeing good utility voltage), or at the manual discretion of the operator. Key aspects of this transition are described below.

1) No synchronizer on CHP Generators

There are a small number of preparatory commands sent from the microgrid controller to prepare for a planned, seamless transition from islanded to grid-tied operation. A synchronous close command is sent to the interconnection breaker, but the CHP generators do not have controls to synchronize with a remote utility source.

The CHP generators have consistent variations in output frequency, which allow the microgrid system to synchronize frequency and phase angle with the utility system. The voltage of both the CHP generators and the utility system are consistently maintained at comparable levels and do not require adjustment. The interconnection breaker relay monitors the two systems and closes the breaker when they are synchronized.

To control closing, the interconnection breaker relay has a short timeout in which the system must synchronized, or the command expires. The timeout is set based on the tested and calculated maximum time to synchronize.

2) Any active CHP generators must maintain 50% output.

The CHP generators will run at no lower than half capacity when grid-tied. When islanded, they can fluctuate based on load, but the microgrid controller uses the BESS to increase the load on the generators in cases where the normal customer load is too low to satisfy the 50% requirement.

Prior to closing the interconnection breaker, the controller sets each CHP generators' power setpoint to 50% output. In most scenarios, this will cause the generator to ramp down output as soon as it is grid-tied. This ramp down behavior is preferred because it results in power flow from the utility.

3) Power cannot be exported back to the utility.

In some scenarios, if the customer loads are too low, the CHP generator output will ramp *up* to 50% output when the microgrid is reconnected to the utility. This behavior is not ideal because of utility prohibition on power export. There are protective relays monitoring net power import that will trip off all DERs (but maintain the customer loads) if power is exported back to the utility for too long.

C. *Unplanned Transitions from Grid-Tied to Islanded Operation*

Seamless unplanned transitions from grid-tied to islanded operation are achieved using a combination of protective relaying and microgrid controls.

The microgrid controller continuously evaluates if the microgrid is capable of transitioning to islanded operation if an event were to occur. This includes two significant considerations: whether the online DERs could supply the present loads in steady-state islanded operation, and how the online DERs would perform during the transient event and recover thereafter. To determine the conditions in which DERs could adequately ride through the event and supply the system load, power system analysis was performed and later validated through system testing. The analysis considered various combinations of online DERs and load levels, and the performance was evaluated during and after simulated system events. The criteria determined from this power system analysis were programmed into the microgrid controller. Considering these criteria, the controller continuously evaluates the system conditions to determine if successful recovery from a system event would be expected. This decision is then used to control relay protection behavior by enabling or disabling the seamless unplanned transfer protection tripping functions.

When the relays' seamless unplanned transfer protection functions are enabled by the microgrid controller, they are set to detect system events and respond promptly by tripping the interconnection breaker. The relays use a combination of transfer trip signals and local logic incorporating directional overcurrent, undervoltage, underfrequency, overfrequency, and rate-of-change of frequency (ROCOF) functions. This combination enables the relay to securely, sensitively, and rapidly detect system faults and loss of source, triggering a trip of the interconnection breaker and transition to islanded operation.

When the relays' seamless unplanned transfer protection functions are disabled by the microgrid controller (e.g., in conditions where online DERs are not capable of supplying present loads), the interconnection breaker remains closed through the system events. Various other protective functions will disconnect DERs individually to clear the DERs contributions to system faults and for anti-islanding protection. This behavior keeps loads connected to the bulk system, providing an opportunity for utility system reclosing functions to restore power rapidly after a temporary system fault.

D. *Successful Seamless Unplanned Transition Event*

A few months after the microgrid was successfully commissioned, the microgrid experienced a real utility event and successfully transitioned seamlessly from grid-tied to islanded operation. On July 15, 2019, a fault occurred on the sub-transmission circuit feeding the microgrid system. The microgrid DERs supplied fault current, which was detected promptly by the undervoltage-supervised directional overcurrent element in the interconnection relay. Fig. 2 shows relay current and voltage measurements during the fault, including measurements prior to the event and after the microgrid has separated.

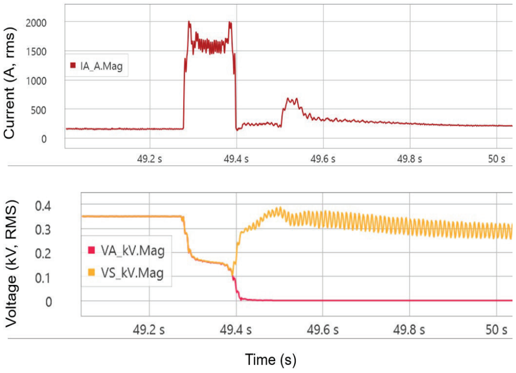

Figure 2. Microgrid DER Current (top) and Voltage (bottom) vs. Time

This figure shows the increased DER current while contributing to the fault. After approximately six power system cycles, the interconnection breaker opens to disconnect the microgrid from the bulk system. During the fault, the DER voltage is depressed. Following the disconnection of the microgrid from the bulk system, the microgrid voltage recovers while the utility voltage collapses.

After this successful operation, the microgrid operated islanded for approximately two hours. The microgrid was then successfully re-synchronized with the utility to return to grid-tied operation.

III. LESSONS LEARNED ON FACILITATING SEAMLESS TRANSITIONS

The authors learned about aspects of microgrids that help and hinder seamless planned and unplanned microgrid transitions between grid-tied and islanded operation. Some lessons learned can be generalized to identify aspects of microgrid systems which facilitate successful seamless transitions.

A. *Power System Analytical Simulations*

To successfully execute seamless transitions between grid-tied and islanded operation, extensive power system analysis is essential.

Seamless transitions from grid-tied to islanded operation in planned scenarios require an understanding of how DERs will transition between modes of operation, to ensure stable performance before, during, and after the transition. For example, if DERs will transition from grid-following to grid-forming operation when the interconnection breaker opens, the frequency and voltage variation during and after the transition must be assessed. Furthermore, grid-following resources to determine if they can ride through frequency, voltage, and phase angle variations during the transition.

Seamless transitions from grid-tied to islanded operation in unplanned scenarios requires simulation of various DER dispatch and system load scenarios. This transition is particularly challenging to ride through. Simulations can identify which scenarios can result in successful ride-through and seamless transitions, DER ride-through requirements, and protection speed and sensitivity requirements. In the planned scenario, DERs can be configured prior to the transition to improve performance during the transition. In the unplanned scenario, the microgrid must ride through a system event, quickly disconnect from the bulk system, and recover stably. Furthermore, testing this scenario with an integrated system is challenging because intentionally faulting a system is not typically done.

Seamless transitions from islanded to grid-tied operation in planned scenarios require an understanding of how DERs will transition between modes of operation, similar to transitions in the opposite direction. For example, if DERs will transition from grid-forming to grid-following operation when the interconnection breaker closes, the DER performance with phase angle, frequency, and voltage shifts should be evaluated. Avoiding damage to equipment is a primary concern in this transition.

B. DER Characteristics

Characteristics and capabilities of DERs significantly impact the capability of the microgrid to perform seamless planned and unplanned transitions between islanded and grid-tied operation. DER controls, ramp rates, inertia, and ride-through capability all have a significant impact.

DER controls must have specific capabilities to be suitable for seamless planned and unplanned transitions between islanded and grid-tied operation. First, all microgrids require a DER that can operate as grid-forming while islanded. To perform seamless transitions, at least one of the DERs must have both grid-tied and grid-forming (islanded) modes, as well as a way to switch between these modes. In the grid-tied mode, it is desirable that the power output of the DER can be controlled to minimize the step load change during seamless transitions. Second, the DERs must be capable of synchronizing both with the other DERs, with the grid, and across the point of interconnection. DERs must synchronize with the system to operate in parallel with other DERs or the bulk system. This synchronization is typically performed at or physically near the DER terminals, where direct measurements of both the system and DER voltages can be obtained by DER controls while isolated from the system. To seamlessly return from islanded operation to grid-tied operation, the DERs must be capable of synchronizing with the bulk system across a remote point of interconnection.

Ramp rates are the rate at which a DER can change active power output (kW/s). DERs with faster ramp rates are more conducive to seamless transitions between grid-tied and islanded operation. In planned transitions, a fast ramp rate allows the resource to adjust more quickly to the desired set point, which accelerates transitions. In unplanned transitions, faster ramp rates allow DERs to promptly react and adjust power to match system load, allowing the system to recover. Rotating machines designed for efficient power operation often have lower ramp rates, which can hinder performance during microgrid dynamic events like seamless transitions. Battery energy storage systems (BESS) in microgrids often are capable of very fast ramp rates; thus, BESS can be applied to enable and improve system performance in seamless transitions.

Inertia controls the rate that the system frequency changes during system events (e.g. faults or load acceptance) when the system electrical active power demand varies from the machine's prime mover power output. With lower inertia levels, system frequency varies more rapidly with active power mismatches and vice-versa. During seamless transitions there is often a mismatch between DER power output and system demand, causing frequency to change during transitions to islanded operation. In this application, the system inertia is relatively low, which necessitated faster system protection response to achieve seamless unplanned transitions, and precise control to minimize system impact during seamless planned transitions.

The capability of DERs to ride through system events also impacts seamless transitions. If DERs trip offline during these frequency and voltage variations, this can exacerbate generation and load mismatches, challenging system recovery to steady state and resulting in further voltage and frequency decrease. Seamless transitions during unplanned events require DERs to ride through more severe voltage and frequency deviations caused by a system event. IEEE 1547-2018 includes requirements for DER ride through, as defined by Categories I-III [2].

C. Protective Relaying

To successfully execute seamless transitions, effective microgrid protective relaying design is critical. Protective relays play a role in seamless planned and unplanned transitions between grid-tied and islanded operation.

During seamless transitions from grid-tied to islanded operation in planned scenarios, relaying is only required to report measured values and respond to commands to open.

Seamless transitions from grid-tied to islanded operation in unplanned scenarios require fast, precise, and secure relay response. Because microgrids often have low inertia levels, limited DER ramp rates, and constrained DER ride-through capabilities, fast relay response is imperative to allow the microgrid DERs to seamlessly recover into stable microgrid operation. This can be achieved using a combination of protective elements, as previously described in the section II.C. Furthermore, microgrid relaying can monitor for and block seamless transitions for severe system events which could cause microgrid DERs unacceptable stress

During seamless transitions from islanded to grid-tied operation in planned scenarios, relays are required to ensure synchronism between the microgrid system and bulk system is achieved. Microgrid point-of-interconnection relays can both assist in achieving synchronism and verify synchronization is achieved. Relays can help achieve synchronization by reporting voltage and frequency measurements from both sides of the open point-of-interconnection and by sending signals to DER controls in some applications. Synchronism check is also implemented at the point-of-interconnection relay, to only allow the open point to close if the microgrid and bulk systems have adequately matched voltage magnitude, frequency, and phase angle.

D. Controls

The microgrid controller takes advantage of the various monitored and commanded components to achieve seamless transitions. The hierarchy (Fig. 3) allows the supervisory control system to evaluate the overall state of the system and to determine what actions are possible given the observed operating conditions, without the computational burden of having to perform fast-response control. Rather, the supervisory control algorithms focus on whether certain transitions are possible given the load and available generation capacity. The fast-acting portions of the control system can then be configured to provide rapid response to events. The microgrid controller consists of three distributed CPUs, each of which can communicate with the different microgrid assets. This provides additional reliability through redundancy of decision-making and communication.

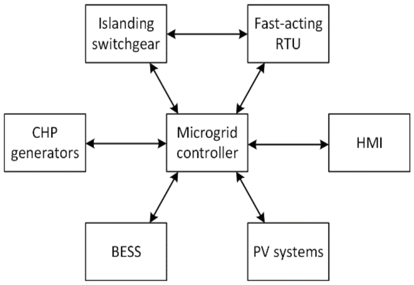

Figure 3. Microgrid control system hierarchy

The distributed control system provides additional benefits over conventional, single-controller architectures. Any of the control CPUs can run the web server that provides visualization into the system (although only one does at any given time). Dynamic reassignment of this functionality between the CPUs allows the operator to monitor the system even if individual control units are taken offline for updates or other modifications. The separation of functionality means that the decision-making algorithms can run on a different CPU than the web server, reducing the computational burden on any one CPU and offering similar ability to migrate the control operations if necessary.

To evaluate if the system is expected to ride through unplanned outages, studies showed the criteria were (1) having two generators running, (2) a net power import of 100 kW or less across the interconnection breaker, (3) having the load less than the combined capacity of the DERs that are online and expected to ride through the event, and (4) verifying that the system was not already transitioning into (or out of) islanded mode.

One of the challenges in performing seamless transitions comes from the intermittency of the loads, particularly the large variation experienced during hockey rink ice production. As mentioned earlier, successful riding through an unplanned outage is contingent on maintaining a net power import of 100 kW or less. During ice creation the loads step up and down by 150 kW, potentially defeating the criteria for allowing the fast-acting RTU (in this case, microprocessor relays) to respond to a utility outage. The BESS is engaged to smooth these variations, largely mitigating the impact of the intermittent ice creation.

E. Interconnection Export Restrictions

Utility limitations on power export can challenge successful seamless transitions.

When performing a planned transition from grid-tied to islanded operation, the microgrid controls reduce the power flow across the point of interconnection to minimize required DER power changes when separating from the grid. Export restrictions and varying load cause the microgrid to typically import power prior to transitions. Consequently, microgrids with export restrictions may see frequency and voltage variations when accepting loads during seamless transitions.

To comply with utility export restrictions, typically, the microgrid is controlled to import power during normal steady state operation. Similar to planned transitions, the microgrid must therefore accept loads when an unplanned transition to islanded operation occurs. Accepting larger loads can challenge the voltage and frequency recovery of the microgrid. If the microgrid is importing excessive power, the system may not be capable of executing a successful unplanned seamless transition to islanded operation.

When performing a planned transition from islanded to grid-tied operation, after reconnecting to the utility, the microgrid controller and DERs must respond quickly to avoid violating export restrictions. For DERs with slow ramp rates, this can be difficult to achieve.

IV. CONCLUSION

The authors recently completed the design and commissioning of the innovative Community Energy Park microgrid in North Bay, Ontario. This system is capable of seamlessly transitioning between grid-tied and islanded operation in both planned and unplanned scenarios. This paper describes how transitions are executed in this application. The authors describe lessons learned in implementing seamless transitions in this and other microgrid projects. Important considerations in implementing microgrids with similar functionality are described, including power system analysis, DER capabilities, protective relaying, controls, and export restrictions.

ACKNOWLEDGMENT

North Bay Hydro Services is a subsidiary of North Bay Hydro. This project and the findings here would not be possible without the gracious trust and respect of the North Bay Hydro Services team. We would like to extend our thanks to Matt Payne, COO of North Bay Hydro and his team.

S&C Electric Company, a market leader in microgrid integration, was responsible for designing, engineering, and constructing the project with North Bay Hydro Services. We are very appreciative of the opportunity to be involved in progressive, innovative industry projects like this one from start to finish. Avis Peterson and Rich Gray were key leaders in making this project and tests successful from beginning to end.

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