Microgrid Controller and Distributed Energy Resource Functionality Verification via Laboratory and Field Verification

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ABSTRACT

A key component of a microgrid system, the microgrid controller is responsible for managing assets to meet the microgrid objectives. This paper evaluates the flexibility of a microgrid controller in different laboratory and field environments so that performance can be evaluated at various end-user community applications and to a wide range of electric grid characteristics. The paper describes the use cases that was used to evaluate the performance of a microgrid controller. The results presented in this paper can inform microgrid controller providers, developers, and utilities, who will benefit from the evaluation of microgrid controllers prior to field deployment.

INTRODUCTION

Increased interest in microgrids is the result of the confluence of a number of important factors 1) Costs of distributed generation of many different types continues to decrease. This includes gas-based generation that has benefited from the lower cost of natural gas as well as renewable generation (solar, wind, hydro), 2) Storage development for many different industries is lowering its cost for the electric power industry. Storage is a key element of a microgrid to provide the flexibility of operation needed, 3) Applications like combined heat and power further improve the economics of local generation and provide the opportunity for local optimization of resources and loads, 4) There continues to be a need for improved resiliency and coordination of local system strategies (e.g. microgrids) with overall grid investments that can result in more optimum overall investment strategies and reduced times to restore power after major events. The increased interest in microgrids as both a system for local energy optimization and for improved resiliency comes with a need for new controller strategies that can help realize these applications. The new controllers should also reflect industry standards and provide a platform for continued innovation. A flexible controller with standard functions and interfaces can expand community opportunities for microgrids.

The paper summarizes the results from a two-year study that was conducted jointly by Electric Power Research Institute (EPRI), Spirae, National Renewable Energy Laboratory (NREL), and EDF R&D. This research which was funded by US Department of Energy (DOE) determined microgrid controller requirements using a use-case approach, then developed, configured, and validated performance of a microgrid controller capable of managing from 1 to 10 megawatts (MW) of aggregated generation capacity. After defining the requirement specifications and developing a generic controller architecture as well as functionality, the microgrid controller was first tested at two premier testing facilities in US so that it can be easily adapted at various end-user community applications and to a wide range of electric grid characteristics. After lab testing was completed, the microgrid controller was configured at EDF's Concept Grid field site and demonstrated the ability of the controller to meet the needs of this system with diverse assets and resiliency requirements.

MICROGRID SYSTEM CONFIGURATION & TEST BED SETUP

A test bed can be set up with software simulation capability only, controller hardware-in-the-loop (CHIL) only, controller and power hardware-in-the-loop (CHIL/PHIL), and hardware. We implemented a site-specific CHIL/PHIL test bed at NREL using an RTDS digital real-time simulator, as illustrated in Figure 1 that uses the actual microgrid controller hardware for CHIL and a representative model of the battery inverter hardware for PHIL. This allowed us to reduce modeling inaccuracies, especially because most proprietary controls embedded within the hardware are not available in the public domain and therefore cannot be accurately modeled. The coincident peak load for the proposed campus microgrid is 24 MW.

The test bed was configured to utilize variety of industry standard communication protocols commonly supported between the microgrid controllers and individual DER assets. The microgrid controller under test, used standard communications protocols including Modbus and DNP3. The majority of the signals were sent using Modbus, and others were sent using DNP3. At the time of testing, it was faster and computationally more efficient to use DNP3 than Modbus to send and receive information from the RTDS. The microgrid controller controls the real and reactive power flow across the PCC breaker and controls the operating modes of the assets based on the state of the microgrid—i.e., whether it is grid-connected, islanded, or transitioning between these two states.

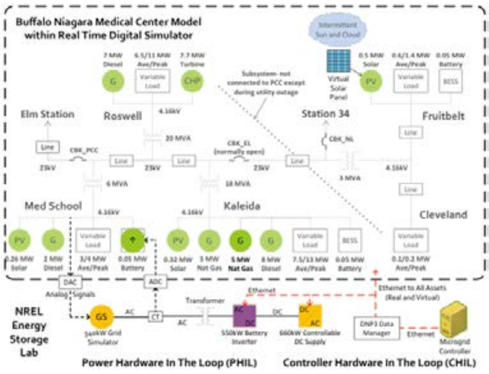


Figure 1. NREL PHIL and CHIL setup

Figure 2 provides a low voltage simplified schematic of EDF concept grid including references to assets utilized. To make Concept Grid even more representative of real distribution networks, EDF has reproduced a residential neighborhood with 5 houses of 20m2 each fitted with smart meters, remote controlled household appliances, reversible heat pumps, micro-wind turbines, photovoltaic panels, terminals for charging electric vehicles, storage systems. This residential neighborhood of sample homes brings together new technologies such as renewable energies, storage and electric mobility. The communication functions are provided by different technologies such as power line carriers (PLC), radio and two separated fiber optics telecommunication networks. The flexible interconnect enables the testing of power management strategies including import/export control, scheduled islanding, grid synchronization and blackstart.

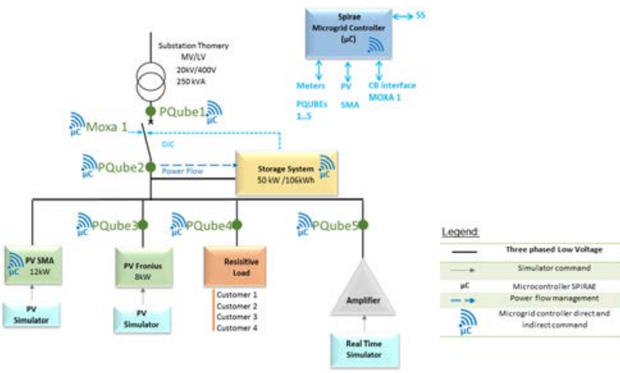


Figure 2. LV simplified schematic of EDF concept grid.

TEST CASES CONSIDERED

Various test cases had been considered to evaluate the compliance of microgrid controller within a laboratory setting at NREL as well as field setting at EDF Concept Grid. The tiered approach with complementary testing platforms, as compared in Table 1, enabled a quantifiable demonstration strategy to test the microgrid controller. The test cases considered at NREL and EDF site are included in Table 1 and Table 2.

Table 1. Test cases matrix for NREL's testing

Test cases		Test objectives
Use Case A: Operating the Microgrid While Connected to the Utility	**A.1** Normal Grid-Connected Operation with No Dispatch (Baseline)	Determine a baseline of the system with no Wave influence
	A.2 Normal Grid-Connected Operation with Dispatch	Demonstrate Wave power dispatch functionality while connected to the utility
Use Case B: Separating the Microgrid from the Utility	**B.1** Planned Separation	Demonstrate Wave utility separation functionality during a planned disconnection
	B.2 Unplanned Separation Due to an External Fault	Demonstrate Wave utility separation functionality during an unplanned disconnection caused by an external single-phase-to-ground fault applied on Phase A
	B.3 Unplanned Separation Due to Loss of Utility	Demonstrate Wave utility separation functionality during an unplanned disconnection caused by a grid outage
Use Case C: Operating the Microgrid While Separated from the Utility	**C.1** Normal Islanded Operation	Demonstrate Wave functionality while separated from the utility
	C.2 Internal Short During Islanded Operation	Demonstrate Wave functionality while separated from the utility with an internal single-phase-to-ground fault applied on Phase A
Use Case D: Connecting the Microgrid to the Utility	**D.1** Reconnection	Demonstrate Wave utility reconnection functionality

Table 2. Test cases matrix for NREL's testing

Test cases			Test objectives
Use Case 1: Set points for active and reactive power flows at the point of coupling when connected to the grid	**TC 1.1** Series of Set Points for the Coupling Point (constant load and PV generation)	Case 1: The system storage **has** the capability to compensate a consumption or generation power flow at the point of coupling in order to fulfill the request	Evaluate the microgrid controller capability in terms of power flow management at the point of coupling for different set points requests
		Case 2: The system storage **has not** the capability to compensate a consumption or generation power flow at the point of coupling in order to fulfill the request	
	TC 1.2 Series of Set Points for the Coupling Point (variable load and PV generation)	Case 1: high level and variable load with constant level of PV generation	Evaluate the microgrid controller capability in terms of power flow management at the point of coupling for different set points requests
		Case 2: high level of variable PV generation and low constant consumption	
		Case 3: variable load and PV generation	
	TC 1.3 Step power variation		Evaluate the microgrid controller capability in terms of power flow management at the point of common coupling for different step power variations
Use Case 2: Scheduled islanding	**TC 2.1** Normal Situation		Observe the microcontroller capabilities in terms of storage SoC, power flow on the microgrid
Use Case 3: Maintain islanding for a given duration	**TC 3.1** Normal Situation	Case 1: the scheduled islanding will be tested with accurate load and generation forecast	Observe the microcontroller capabilities during the islanding operation before the grid reconnection
Use Case 4: Reconnection to the main grid	**TC 4.1** Resynchronization Operation		Observe the microcontroller capabilities of grid resynchronization and reconnection.
Use Case 5: Black Start	**TC 5.1** Black start		Observe the microcontroller capabilities of black start

PERFORMANCE VERIFICATION USING HIL

Following functional requirements outlined by DOE were leveraged in this paper: C1 (Disconnection), C2 (Resynchronization and Reconnection), C3 (Steady-State Frequency Range, Voltage Range, and Power Quality), C4 (Protection), and C5 (Dispatch).

Table 3. Mapping of scenarios to functional requirements

Scenario Description	C1	C2	C3	C4	C5
	Disconnection	Resynchronization and Reconnection	Steady-State Frequency Range, Voltage Range, and Power Quality	Protection	Dispatch
Operating While Connected to the Utility					x
Separating from the Utility	x			x	
Operating While Separated from the Utility			x	x	x
Connecting to the Utility		x			

In Usecase A1, the microgrid controller's dispatch function was disabled, and all dispatchable generation was turned off. In Case A2 case the microgrid controller was set to dispatch based on cost parameters (startup, hourly, operating, stopping, etc.) to achieve the active and reactive set points for PCC power flow. The PCC power flow set points were set to zero for both active and reactive power. The load of all three buildings and the power flows through the PCC circuit breaker are shown as stacked plots in Figure 3. The power flow through the PCC circuit breaker is nonzero for short periods after a load step until the Wave microgrid controller is able to regulate it to zero. The corresponding generation dispatched by the microgrid controller to regulate the PCC power flow to zero is shown as stacked plots in the bottom portion of Figure 3. The microgrid controller dispatched internal combustion engine 1, 2, and the diesel generator 3 for the base load and during peak demand, it dispatched diesel generator 4. Once the demand dropped in the evening, diesel generator 4 was turned off for cost and emission benefits.

The performance of the microgrid controller was evaluated according to the following objectives set forth in FOA 997: (1) survivability, (2) economic operation, and (3) environmental performance. Figure 3 verifies the survivability since all loads were served. The oscillations in real and reactive power during peak load were mainly caused by startup and shut down transients of the assets.

Three test cases were simulated for scenario B to validate the ability of the microgrid controller to successfully island the microgrid under planned and unplanned conditions. The building loads and solar insolation were set to fixed values at the peak load time in Figure 4, and a request to island was input to the control platform. We verified that the control platform brought the power flow across the PCC to zero and that it opened the Elm Station PCC circuit breaker. To confirm stable operation, we verified that the Wave control platform set asset DG3 as the isochronous master and voltage master and that the microgrid operated for several minutes. The top trace shows the disconnect signal issued by the microgrid controller, and the trace that is second from the top shows the voltage on the microgrid side of the PCC breaker. The trace that is second from the bottom shows the current through the PCC breaker. The bottom trace shows the output current of the hardware battery inverter. The microgrid controller reduces the power flow across the PCC to nearly zero prior to islanding to ensure a smooth transition. The simulation results of the microgrid voltage and measured battery inverter current confirm that a smooth transition occurred.

The controller successfully behaved in all the three cases. Only the planned case is shown.

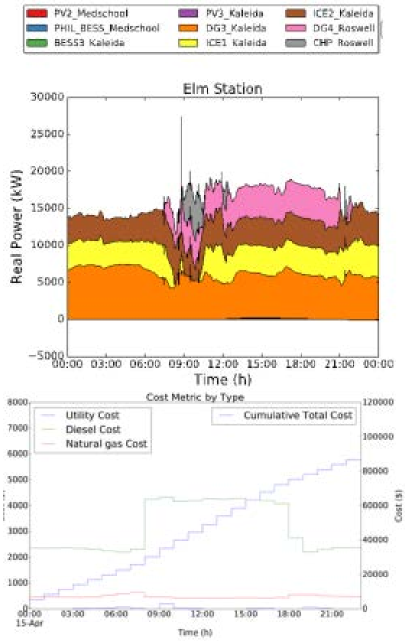


Figure 3. Stacked plots of generation for the three medical campus for Test Case A2

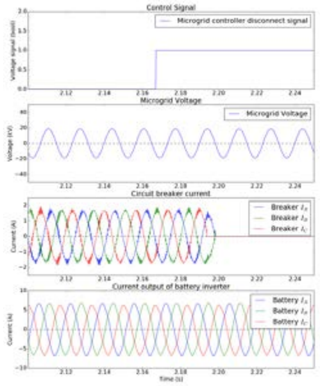


Figure 4. Planned disconnection result for Test case B1

Two test cases were simulated for scenario C to validate the ability of the microgrid controller to dispatch assets for successful islanded operation. For the sake of brevity, only the first test case, i.e. normal islanded operation, is presented here. C2 simulated an internal short during islanded operation, and results are not presented because the Wave microgrid controller did not provide protective functions. The microgrid was set up to operate in islanded mode through a planned islanding event as described in B1. Once islanded, the same load and solar insolation profiles used for A2 were initiated. The generation profiles of all generation—dispatchable and nondispatchable—are shown as a stacked plot in Figure 5. The microgrid controller successfully operated the microgrid in islanded mode under normal conditions by dispatching generation to continuously serve all loads within the microgrid. The oscillations that occur during peak hours are due to the transient behavior of the assets at startup and shut down.

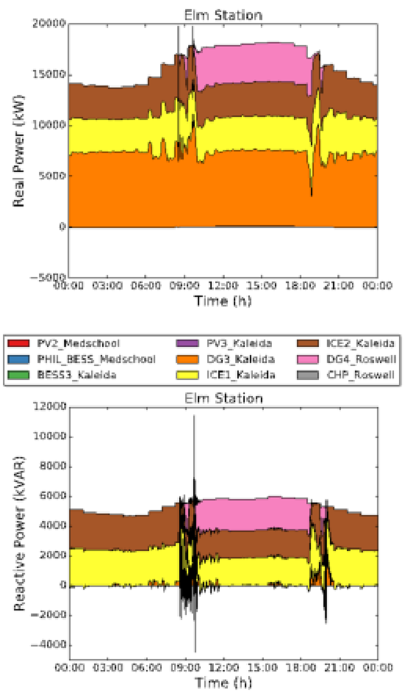


Figure 5. Stacked Plots for Test case C1

One test case was simulated for scenario D to validate the ability of the microgrid controller to reconnect the microgrid to the utility grid as shown in Figure 6. The microgrid was set up to operate in islanded mode, as described in C1, except that the load and solar insolation were set to fixed values encountered during the peak load for the day, similar to B1. The microgrid controller did not provide resynchronization functionality; rather, it relied on the PCC breaker to perform this function, and we therefore implemented controls in the PCC breaker to perform resynchronization. The microgrid controller issued a resynchronization signal to the PCC circuit breaker to start the resynchronization process; and once the voltage, frequency, and phase angle errors between the grid and microgrid got to values that were low enough, the PCC circuit breaker control closed the breaker.

Simulation results for D1 are shown in Figure 8 for a few cycles before and after reconnection. Trace A, at the top, shows the microgrid controller disconnect signal and the PCC circuit breaker status. The microgrid controller disconnect signal is zero, indicating that the Wave microgrid controller had previously issued a signal to reconnect. Trace B shows both the utility grid and microgrid voltages for Phase A, and Trace C shows the current through the PCC circuit breaker. Trace D shows the measured output current of the hardware battery storage inverter, scaled from the hardware rating of 540 kW/480 V AC to the simulated rating of 50 kW/4.16 kV. The current transients after reconnection are larger than expected and has not yet been analyzed fully, but we observed that it takes some time for the controller's dispatch assignments to finalize, which could be one of the main reasons.

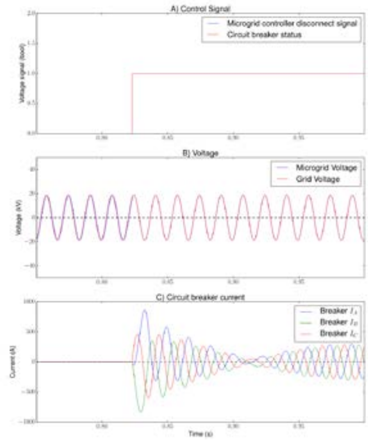
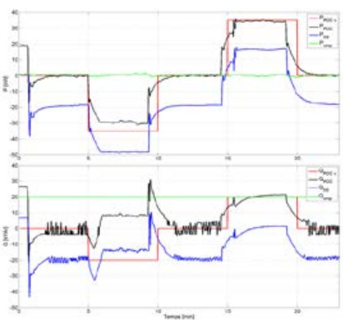


Figure 6. Test case D1 (reconnection) within a few cycles

PERFORMANCE VERIFICATION @EDF CONCEPT GRID

In the EDF Concept grid tests, the battery storage system was used as voltage and frequency master in islanding mode. In grid connected mode, the charging and discharging of the battery was controlled by the microgrid controller. The LV circuit breaker located downstream from the transformer was considered as the PCC. The PCC flows for some of the test cases in TC1.1 are shown in Figure 7.

Transitions from grid connected to islanding mode and vice-versa were managed indirectly by the microgrid controller. The microgrid controller sent a command using Modbus protocol. Then an operator manually launched the automatic islanding procedure on the storage system. The storage system then controlled the opening and closing of the circuit breaker. Two PV inverters were used as current sources. The LV amplifier was used either as a load or as a current source, depending on the test case needs. A resistive load was used as an aggregated consumption. The battery islanding controller was in charge of the real time battery inverter operation (maintaining voltage and frequency stability). The microgrid controller was able to communicate with the islanding controller and only the PV inverter, in order to optimize the overall microgrid operation.



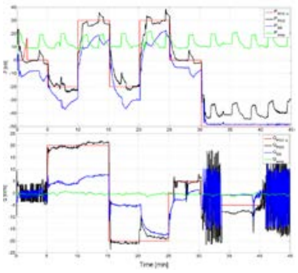


Figure 7. Active and Reactive Power Measured at PCC for UC1.1

The black start capabilities are demonstrated in Figure 8. The graphs show only the active and reactive power supplied by the storage system during the blackstart. The Wave issued the blackstart decision. An operator demanded the blackstart to the storage system. After the 2nd min of the recording, the 39 kW load was connected, followed by the PV Fronius at 2 minutes and 36 seconds, injecting 8 kW and then the PV SMA at the 3rd minute, injecting 12 kW

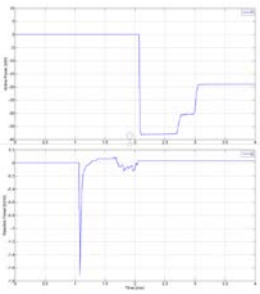


Figure 8. Active and reactive power measured by EDF for TC 5.1 – Black Start

LESSONS LEARNT & CONCLUSIONS

HIL Testing: The proposed test methodology enabled us to evaluate the functional requirements in FOA 997. However, some of these requirements may not be achieved by the microgrid controller itself. For example, the microgrid controller relies on the synchronization relay of the PCC circuit breaker to ensure that the grid reconnection occurs only when amplitude, frequency, and phase angle differences between the microgrid voltage and utility grid voltage are within the desired limits provided by the FOA 997 requirements. PHIL simulation under abnormal conditions was challenging because the controllable AC and DC power supplies were prone to tripping off when they needed to operate outside the bounds of their protective settings. The appropriate settings used to simulate abnormal conditions while protecting laboratory equipment are topics for further investigation. We used frequency meters from the standard library available in RSCAD, and results were sensitive to whether we used a three-phase meter based on a phase-locked loop or a single-phase meter based on zero crossings. Further investigation is needed to determine which method is more reliable for microgrid simulations. Simulation results are influenced by the coefficients used in the Wave platform's proportional integral (PI) controllers and by the design of the generator controllers implemented. This was especially noticeable during mode transitions—i.e., when a generator transitions from voltage/frequency master mode to baseload mode. Consequently, the generator controller design needs to be refined to more accurately represent real-world generators. We also recommend a lower ratio of real time to simulation time steps for accelerated simulations because not all transients settled within the 2-minute simulation time step that we selected to represent 1 hour in real time.

Field Tests: The microgrid controller demonstrated its capability to communicate with all the assets in real time. With regard to the functional capabilities of the microgrid controller, the Use Case 1 was the most relevant test compared to the other proposed cases during the test experiment. Generally, the time response of the microgrid controller to reach an active and reactive power setpoint at the PCC took a few minutes. While with a high level of variation (power flow demand and/or load/production), the controller was not able to manage the power flow at the point of common coupling. During the testing period, the controller gain had to be adjusted, in order to more quickly reach the request at the point of common coupling. However, oscillations and overshoots have been observed due to the setting modification applied to the controller. The setting of the PID regulation may need to be adapted in order to follow the requested power flow more properly.

EDF designed the test plan in order to test the microcontroller comprehensively. Each test case was created to reveal, step by step, the different performances of the tested device. This requires a predefined set of settings that do not change during the tests or from one test to another. On the other hand, controller had an adaptive approach, learning, adapting and applying changes to the optimizers and to internal settings during the tests. Although this approach helped to better perform the controller, more time should have been allocated for a tuning phase for this approach, in order to perform the test cases with an unchanged set of parameters. During the tests, microgrid controller was found to have different optimizers available which refers to the way the controller treats the PVs and the storage system priorities and power management. More study on the optimizers should have been done for desirable power dispatch performance through proper selection of these optimizers.

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