

Canadian Renewable Energy Laboratory (CANREL)- A Testbed for Microgrids

Ehsan Nasr-Azadani, *Member, IEEE*, Peter Su, Wenda Zheng, Janos Rajda, *Member, IEEE*, Claudio Cañizares, *Fellow, IEEE*, Mehrdad Kazerani, *Senior Member, IEEE*, Erik Veneman, Stephen Cress, Michael Wittemund, Manoj Rao Manjunath, Nicolas Wrathall

Abstract—This paper presents a test facility for design validation of microgrids with high penetration of renewable energy, developed as a joint effort with industry, government, and academia. The Canadian Renewable Energy Laboratory (CANREL) described here is a physical simulation tool for the design, development, and performance testing of islanded and grid-connected microgrid projects. CANREL is equipped with a diesel generator, different renewable energy sources, various renewable energy generation simulators and physical systems, a bidirectional power flow grid simulator, a battery-based energy storage system, and controllable RLC and electronic test loads, for the design and testing of a variety of microgrid solutions. The test facility provides project performance demonstration and validation services at each stage of a microgrid project development to help utilities and project developers to reduce risks. It is also a physical simulation tool for benchmarking microgrid equipment and controllers for research and development purposes. Some facility-test results are presented in this paper to demonstrate the capabilities of CANREL for simulating a wide range of scenarios.

Index Terms—Microgrid, renewable energy, testbed, microgrid stability, microgrid control.

I. INTRODUCTION

THERE is a need in the electricity sector to integrate renewable energy resources into existing microgrids dominated by diesel generation, while maintaining the desired performance, reliability, and stability of the system. Although renewables can bring significant benefits to microgrids, there are some technical aspects and challenges, such as stability, protection, and reliability, that must be understood and addressed to ensure adequate system performance [1]–[3].

Presently, there are several demonstration and pilot projects attempting to integrate renewable energy resources into islanded microgrid systems as discussed in [4], where the integration of renewable energy resources in Canadian remote community microgrids are discussed. For example, communities in Northern Ontario, such as Deer Lake and Fort

Severn, have on-going projects to deploy Photo-Voltaic (PV) and hybrid systems to reduce diesel fuel consumption. Also, the remote mine at Diavik, in the Northwest Territories, has installed a wind farm to reduce fuel consumption, and the Northwest Territories Power Corporation has installed a solar/battery system in Coville Lake [5].

For utilities operating islanded microgrids such as microgrids in remote communities, grid stability and system performance are two main challenges when increasing renewable energy penetration. On the other hand, grid-tied communities face different challenges related to improving the resiliency of critical infrastructure. Moreover, since microgrids are a relatively new concept for utilities, engineers and end-users, operating challenges are not well understood. Thus, microgrid demonstration projects and testbed facilities with high penetration of renewables allow utilities to study and address the challenges before large-scale deployments.

During the last decade, several microgrid testbed facilities have been developed in different countries, focusing on operation of various Distributed Energy Resources (DERs) to allow microgrid research and development for actual microgrid deployments. For example, in North America, the National Renewable Energy Laboratory (NREL) has developed various simulators such as a grid simulator, a PV simulator, and a hardware-in-the loop testbed focusing on the characteristics of DERs [6]. The Consortium for Electric Reliability Technology Solutions (CERTS) has a microgrid demonstration testbed with three feeders and loads to demonstrate the integration of three micro turbines into a microgrid based on droop [7]; this testbed does not include emulators or an energy management system, and it is focused on seamless transition between grid-connected and off-grid modes and decentralized control. The Alaska Center for Energy and Power has developed a microgrid testbed including various components such as a wind turbine emulator based on an induction generator, a Battery Energy Storage System (BESS) with a lead acid battery bank, a dc power supply, and a diesel generator, focusing on off-grid applications [8]. The Idaho National Laboratory (INL) has a 300 kW microgrid testbed, including solar panels, energy storage systems, load banks, smart inverters, a power distribution system, a small-scale grid simulator, and multiple switchgear sets; the main focus of the INL testbed is on military applications, simulating the integration of renewable energy resources in microgrids [9], [10]. The DeMoTec microgrid is a 200 kW facility in Germany, that focuses on electrification with renewable energy resources, and it has a

This work was supported by Canadian Solar Inc and Ontario Ministry of Energy's Smart Grid Fund.

Ehsan Nasr-Azadani, Peter. Su, and Wenda. Zheng are with Canadian Solar Inc, Guelph, Canada. (e-mail:ehsan.nasr@canadiansolar.com; enas-raza@uwaterloo.ca) (see <http://www.Canadiansolar.com>).

Janos Rajda is with RYDA design and service Inc.

Claudio Cañizares and Mehrdad Kazerani are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Canada.

Erik Veneman, Michael Wittemund, and Manoj Rao Manjunath are with Guelph Hydro Electric Systems Inc., Guelph, Canada.

Nicolas Wrathall and Stephen Cress are with Kinectrics Inc, Ontario, Canada.

distribution line simulator to investigate the basic issues of DERs in interconnected grids [11]. Most of these microgrid demonstration projects focus on potential benefits of renewable energy resources and the integration of DERs, and are not in general sufficiently flexible to test and assess various control and protection strategies; however, some do allow to carry out microgrid control and protection testing.

There are also several small scale microgrid labs in various research institutes and universities across the world [10]–[16]. For example, the University of Texas at Arlington has developed small-scale testbeds which comprise three independent microgrids, with 24 V dc and 120 V ac buses; it contains lead acid batteries, solar systems, wind turbines, and a fuel cell, connected to the dc buses, and includes dc/ac inverters, a programmable load, and a diesel generator, connected to the ac bus, using a National Instrument (NI) controller to control the testbeds for research purposes [12]. There is also an Association of European Distributed Energy Resources Laboratories (DERlab), which is a cluster of DER laboratories that provide services for testing and validations of DERs [17]. Most of the facilities of DERlab's members are equipped with energy storage systems, PV systems, and wind turbines, for research and development services [10], [11], [18], [19]. In China, a flexible and reconfigurable microgrid testbed that provides various configurations with DERs for grid-connected applications is presented in [14]. There is also a microgrid testbed developed at Hefei University of Technology (HFUT) that includes various DERs [15]. Furthermore, an integrated microgrid testbed has been constructed in Zhejiang Electric Power Test and Research Institute, comprising a diesel generator, a flywheel, fault simulators, and PV and battery systems [16], which focuses on microgrid control strategies; some experimental results for the testbed are presented in [16]. Most of these microgrid testbeds are generally small-scale facilities, focusing mainly on research, control testing and development, which do not allow to address some of the practical needs in industry and remote communities.

Based on the aforementioned issues with existing microgrid demonstration and testbed facilities, there is a clear need for developing of a microgrid testbed that includes various simulators, actual renewable resources, and diesel generators with different operating modes, to better understand and address the technical aspects and challenges associated with microgrids. Therefore, this paper presents a novel microgrid testbed to study technical issues such as stability, power quality, protection, control, and islanding capability of microgrids. The testbed described herein was developed by Canadian Solar in partnership with several remote and rural communities throughout Northern Ontario, universities, a local utility, and engineering firms and is the first of its kind in Canada. The Canadian Renewable Energy Laboratory (CANREL) is equipped with a diesel generator, a wind turbine and PV system, PV and wind resource simulators, a grid simulator, a battery-based energy storage system, and various test loads, to facilitate the design and testing of microgrid solutions with various configurations. The main objectives of CANREL and the contributions of the work presented here are the following:

- Since each smart microgrid system has its own mix of

supply and demand and renewable resource characteristics, CANREL allows to simulate each proposed renewable energy-based microgrid with its unique characteristics and under near real-life conditions, considering the inputs from existing microgrid demonstrations projects, as demonstrated here.

- It is shown here that CANREL provides a testbed for DERs and microgrid control systems to assess innovations on energy management technologies and energy services. A hierarchical-based control approach is proposed and described for CANREL for stable power balancing and goal-oriented energy management systems, both for islanded and grid-tied solutions.
- CANREL provides hardware simulations for both off-grid and grid-connected systems and for the transition between these two modes. The hardware simulations shown here demonstrate the assessment of technical challenges such as stability and power quality of islanded microgrids, which is an issue for utilities (e.g., Hydro One Remote Communities, in Ontario, Canada).

The rest of paper is organized as follows: The testbed facility structure and components are presented in Section II. The modes of operation of the microgrid testbed and its control systems are discussed in Sections III and IV, respectively. Several facility-test results are presented and discussed in Section V. Finally, Section VI highlights the main conclusions of this paper.

II. TESTBED STRUCTURE

The CANREL testbed was constructed utilizing a container approach as illustrated in Fig. 1, and the electrical diagram is shown in Fig. 2. The facility is a low voltage (600 V) ac microgrid, connected to a local utility grid (Guelph Hydro) through a 13.8 kV-600/347 V (delta-wye-gnd) power transformer. There are two feeders connected to the main breaker CB300, supplying a microgrid bus via a microgrid breaker CB 301, and a service bus via a service bus breaker CB302. A grid simulator, which is connected to the microgrid bus via a grid simulator breaker C205, can act as ac power source or ac power sink. The CB301 is considered as a Point of Common Coupling (PCC) for microgrid test cases. Note that one side of the grid simulator, wind simulator, and PV simulator is connected to the service bus and the other side is connected to the microgrid bus. The system is also equipped with protection relays and a complete data acquisition and power quality meter system for each DER and the tie line. The digital data acquisition system includes fifteen power quality meters, providing detailed voltage and current waveforms for events, and transfers all data through Modbus TCP/IP to a central data aggregator for SCADA applications. There were several conceptual topologies considered at planning stages such as multiple buses; however, since the main focus of CANREL is on renewable energy penetration and microgrid control systems, a two-bus system was implemented with the provision of adding a line simulator between two microgrid buses. As shown in Fig. 3, CANREL is equipped with various components, described in some detail next.



Fig. 1: CANREL containerized testbed.

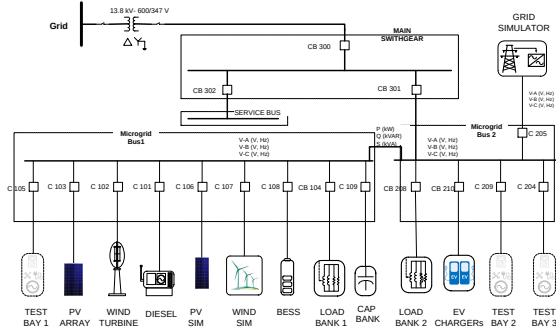


Fig. 2: CANREL one-line diagram.

A. Grid Simulator

The grid simulator is a 270 kVA ac source used to represent the utility grid. It is an inverter-based grid simulator with an internal isolation transformer with bi-directional power flow capability. It can act as an ac power source or ac power sink, and is used to test CANREL subsystem's control mode transitions (grid-connect to islanded mode and vice-versa), grid fault ride-through, and transients and harmonics in the microgrid assets. The grid simulator is able to simulate grid frequency and voltage abnormalities, such as voltage sags and swells for different fault scenarios, and inject harmonics into the microgrid for power quality and stability assessment. The grid simulator has been sized as the largest unit in CANREL to accommodate the testing of other inverters, as per standards such as IEEE 1547.1 [20] or UL 1741 [21]. It is important to note, however, that there is a limit on the current contribution from the inverter-based grid simulator when simulating fault scenarios or protection applications.

B. Wind System

CANREL is equipped with a 100 kW wind-turbine simulator that dynamically simulates the active and reactive power output of a wind turbine or other resources by following pre-loaded P and Q profiles. It is an inverter-based wind-turbine simulator, operated at 480 V with two 100 kW back-to-back inverters, filters, and two isolation transformers. One side of the wind-turbine simulator is connected to the service bus and the other side is connected to the microgrid bus. The wind-turbine simulator has bidirectional power flow capabilities and can act as an ac power source (e.g., wind-turbine mode), as

well as an ac power sink (e.g., dynamic load bank). The inverter at the microgrid bus simulates the wind generation profile while the inverter at the service bus performs as a dc source.

CANREL also has a 3 kW vertical axis wind-turbine generator. It consists of a permanent magnet generator with a single-phase inverter connected to a 240/600 V transformer. The data gathered by the actual wind-turbine generator can be scaled up and used in the wind-turbine simulator.

C. PV System

The PV simulator consists of PV array system simulator, PV inverters, and isolation transformers. The PV array simulator is a software-controlled dc source that simulates I-V and P-V curves of a PV array system. The PV array simulator consists of 6 units of 15 kW dc, rated at 1000 V, with total capacity of 90 kW, and is connected to three string PV inverters, with total capacity of 100 kW. The simulator has a utility grid-facing ac interface and a dc output which interfaces with the PV inverters. Irradiation, temperature, shading, and other parameters can be preloaded into the simulator to simulate the behaviour of an actual PV array. The PV inverters are equipped with a Maximum Power Point Tracking (MPPT) control and external PQ curtailment control.

There is also a 10 kW actual roof-top PV system, which includes 40 Canadian Solar PV panels CS6P-260P that cover the roof of two front rooms. The rated dc bus is 600 V, and the three-phase, 208 V PV inverter is connected through a step-up transformer to the microgrid bus. The data gathered by the actual PV system can be scaled up and used in the PV simulator.

D. Energy Storage System

The BESS consists of a 200 kWh lithium-ion battery pack, equipped with a battery management system, and a 200 kVA bidirectional Power Conversion Systems (PCS). The BESS has fast system response capability and supports bidirectional active and reactive power flows. The BESS can operate as a grid-forming and grid-following unit and has black-start capability. The facility also includes a test bay for other dynamic energy storage technologies, such as super-capacitor or flywheel energy storage, with a rated power of up to 250 kVA.

E. Diesel Generator

CANREL has a 90 kW diesel generator set directly connected to the microgrid bus at 600 V, with a diesel-engine prime mover, synchronous generator, and associated controllers. The diesel generator has black start capability to act as a grid-forming unit and has synchronizing capability in order to connect to the grid and grid simulator. The generator is able to be operated in isochronous mode, droop mode, and PQ mode with remote control capability.

F. Programmable Load Banks

There are two programmable load banks with the capacity of 250 kVA. Each programmable load bank has resistive (0-100 kW) and inductive (0-75 kVar) load elements, which can be controlled remotely to simulate step changes in the load with various power factors and can accept various actual load profile entries. Three-phase, single-phase, and unbalanced load profiles can be implemented using the load bank controller.

G. Capacitor Bank

The facility has a 30 kVar, three-phase, 600 V capacitor bank to simulate capacitive inrush current scenarios and provide reactive power for certain load profiles.

H. Electric Vehicle Charger

Two 7.2 kW electric vehicle chargers are connected to the microgrid bus serving as a test load to assess microgrid resources' response to electrical vehicle loads.

I. Microgrid Control System

The measured data of voltage and current of all of aforementioned assets is collected by the data aggregator system, and is transferred to the Microgrid Control System (MCS). The MCS has a hierarchical structure and has various layers of controls, a high-speed control layer to manage microgrid bus voltage and frequency, and a slower long-term control layer to optimize microgrid operations, such as minimization of cost and maximization of harvested renewable energy. The Energy Management System (EMS) is part of the MCS, as discussed in detail in Section IV.

III. OPERATING MODES

CANREL can be operated in four modes: (i) islanded, (ii) grid-connected utilizing the grid simulator, (iii) utility grid-connected, and (iv) transition, as described next.

A. Islanded Mode

In this mode, CB301 in Fig. 2 is open, and one of the grid-forming units, i.e., diesel generator or BESS, has to energize the microgrid bus. Once a grid-forming unit energizes and establishes the microgrid voltage and frequency, other assets in grid-following mode are synchronized to the microgrid bus. Note that each asset has its own synchronizing controller in order to synchronize to the bus. Different combinations of the aforementioned assets including the BESS, diesel generator, PV system, wind system, and load banks can be tested in this mode.

B. Grid-Connected Through Grid Simulator Mode

In this mode, CB301 is open. The grid simulator can then be utilized to black-start the microgrid and energize the microgrid bus; other assets in grid-following mode (e.g., wind and solar systems), as well as the BESS and diesel generator in PQ mode can be synchronized to the microgrid bus. There is also another possible operating mode, in which the grid simulator

breaker C205 is equipped with a synch-relay such that the entire microgrid can synchronize to the grid simulator once the voltage, frequency, and phase angle are within the allowable range, which are managed by the MCS. Different load and generation profiles and fault scenarios can be simulated and investigated in this mode.

C. Grid-Connected Mode

In this mode, CB301 is closed, and the microgrid acts as a virtual power plant. In this mode, the microgrid bus is energized, and other assets are synchronized to the microgrid bus. The microgrid can be operated based on different objectives such as cost minimization, renewable energy penetration maximization, and voltage and frequency regulation through the MCS. It is noteworthy to mention that CANREL has the capacity to export up to 500 kW to the utility grid.

D. Transition Mode

The transitions between islanded and grid-connected modes of operation is coordinated and controlled by the MCS, and is performed by the utility grid breaker CB301. The MCS controls voltage, frequency, and phase angle of the microgrid bus and ensures that the microgrid is synchronized to the utility grid before closing breaker CB301. The transition from islanded to grid-connected through grid simulator is carried out by the grid simulator contactor C205. Since only one grid-forming unit should energize the microgrid bus, a key-interlock and control-interlock are in place to ensure safe operation.

The transition from grid-connected to islanded mode can be planned or unplanned. CANREL can support both transitions through the MCS and PCC protection relay. Initiating events can be triggered by an operator or by an unplanned trigger from the protective relay.

IV. MICROGRID CONTROL SYSTEM

CANREL has a hierarchical-based MCS approach to control and manage the microgrid assets, similar to the general microgrid control approach described in [22]. The MCS has three layers of control for various modes, as illustrated in Fig. 4, and described next.

A. Local Control (Primary Control)

The first level of control for each DER unit is referred to as the primary control, as per [22]. This level of control is decentralized and each DER unit has its own primary control associated with its technology. In the case of the diesel generator, voltage and frequency control and power sharing are performed by a voltage regulator and a governor. This generator can be operated in droop, PQ, and isochronous modes. DER inverters also have their own local primary controls, such as MPPT control of the PV inverters, constant active and reactive control, and voltage-frequency droop control for the BESS. The inner control loops of voltage, current, and power sharing are part of the primary control for these assets.

If the MCS is deactivated, the operator should set each asset in a proper mode to assure system stability. In this case, the

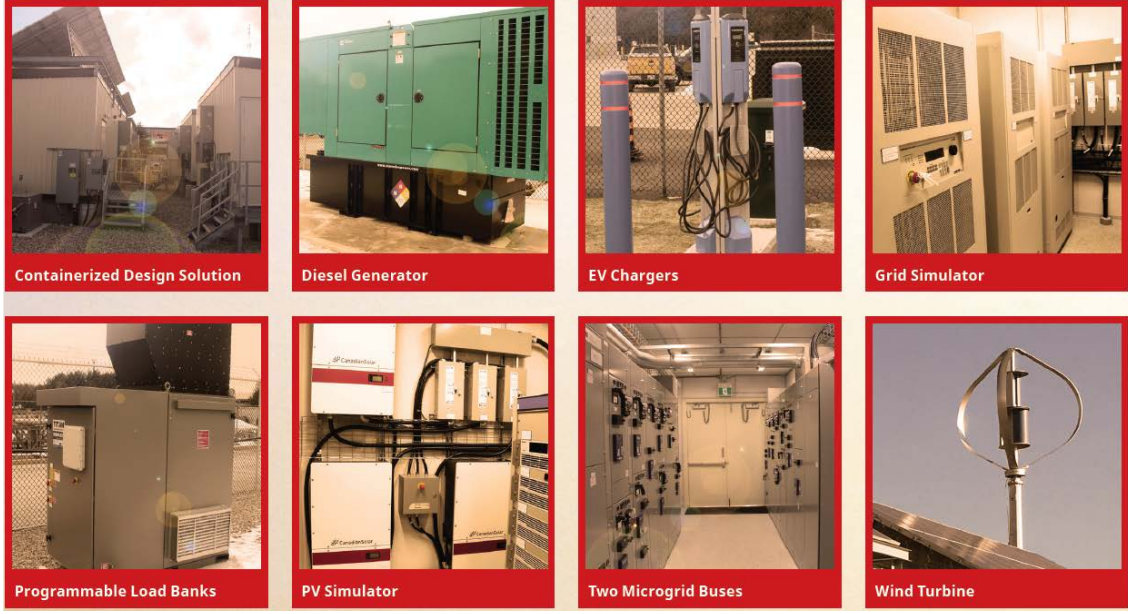


Fig. 3: CANREL system components.

microgrid can be operated autonomously based on only local primary control without having layers of control, using droop controls as in [7]. However, the stability of the microgrid and cost optimization cannot be guaranteed without secondary and tertiary controls. CANREL provides a control interface layer at the local control level in order to communicate with secondary controls. Since DERs at CANREL use different commercial communication protocols (e.g., Modbus TCP/IP, analog I/O, and Modbus RS485), this interface provides a gateway to access the controllable units. It should be mentioned that CANREL also has a control test bay to assess third party control systems, particularly secondary and tertiary controls, through which these control systems can access the local control of controllable units through the control interface.

B. Microgrid-forming Control System (Secondary Control)

This layer of control monitors frequency and voltage at the microgrid bus, adjusting the frequency and voltage, and coordinating the operation of DERs by overwriting their set points. This layer ensures that the voltage and frequency at the microgrid bus are within the allowable range, and maintains the stability of the system both in islanded and grid-connected mode, coordinated with the protection system.

The transition from grid-connected mode to islanded mode can be initiated manually by an operator or through the MCS, triggered by unplanned grid power quality or voltage events through protection relays. Furthermore, this layer of control is in charge of reconnecting the microgrid, i.e., the transition from islanded mode to grid-connected mode, by controlling the voltage, frequency, and phase angle at the microgrid bus, coordinated with a synch-check relay.

C. EMS (Tertiary Control)

The EMS defines the DER set points and acts as a tertiary control level, independent of the aforementioned secondary

control system. It receives the status of all generators and loads, the state of charge of the BESS, and available power and energy from each DER and energy storage system through the data aggregator. The operational limits, stability constraints, and spinning reserve requirements of the microgrid are set by the operator.

1) *Islanded Mode:* Since CANREL focuses on renewable energy resources integration, the objective of the EMS in islanded mode is to harvest the maximum amount of renewable energy, minimizing the diesel fuel consumption, taking into account weather data and microgrid load demand. Depending on the operation of the diesel generator and the state of charge of the battery, the EMS coordinates the local controllers' set points to allow maximizing renewable power penetration levels up to 100% in islanded mode. The EMS calculates a subset of control commands based on an optimization model, defining the DER control set points every 5 minutes.

2) *Grid-Connected Mode:* When the microgrid is in grid-connected mode, the EMS controls active and reactive power at the PCC. Once the EMS receives all required information, it adjusts the DERs' outputs within operating limits to meet one of the following control objectives at the PCC:

- Real power export/import.
- Reactive power export/ import.
- Power factor at the PCC.
- Operating reserve available to the utility.

The EMS provides Volt/Var control by controlling the microgrid assets to achieve the desired V/Q objectives in grid-connected mode. It also has a cost optimization feature to optimize the operation of the assets based on supply energy price and operating cost of DERs. It should be mentioned that the EMS control system has the ability to regulate voltage and frequency at the PCC. In this case, the EMS acts as the secondary control system of the microgrid.

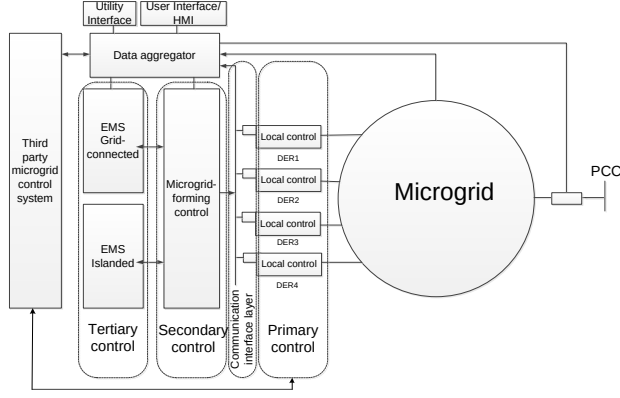


Fig. 4: CANREL Microgrid Control System (MCS) structure.

V. TEST RESULTS

Two sets of tests were performed during and after the commissioning: functional and performance tests. Functional testing included the following tests during the commissioning stage of CANREL: (i) communication systems, (ii) SCADA system, (iii) DER assets, (iv) transformers, (v) switchgear, (vi) protective relays and power quality meters, (vii) grounding, (viii) cables and wires, (ix) low-voltage breakers, and (x) motor control centre and utility interlocks. These tests were performed in early 2017, before commissioning of the site. On the other hand, the performance tests allowed to demonstrate the performance of the DERS, MCS, and system for multiple DER combinations: (i) system black start, (ii) voltage and frequency performance (30 minute load profile), (iii) dynamic system response, (iv) synchronization to existing voltage source, (v) utility transition mode, (vi) grid simulator transition mode, (vii) power flow control, (viii) unbalanced load, and (ix) power quality. The performance tests started in April 2017, leading to various insightful results; hence, some voltage, frequency, and mode-transition tests under performance tests are presented.

The performance tests were designed to ensure that the controllers and EMS were operating as designed, and were able to control assets under various configurations and scenarios. These tests allow to evaluate the integration of multiple assets for various load profiles and renewable sources. Sixteen voltage and frequency performance tests were identified and designed. The voltage and frequency ride-through settings based on IEEE 1547.4 were applied to the main relay at the PCC. Since there are ongoing efforts to develop testing procedures for microgrid controls, the performance test results should help in the development of industry standards. In this paper, the results of three voltage and frequency performance tests and one mode-transition case are presented.

A. Low Renewable Penetration

The Test A was designed for the operation of microgrid in islanded mode with low PV penetration levels. The objective of this test was to evaluate the voltage and frequency performance with low PV level and load step changes. This test allows assessing the typical deployment of renewables in remote communities with low renewable energy penetration, as in the

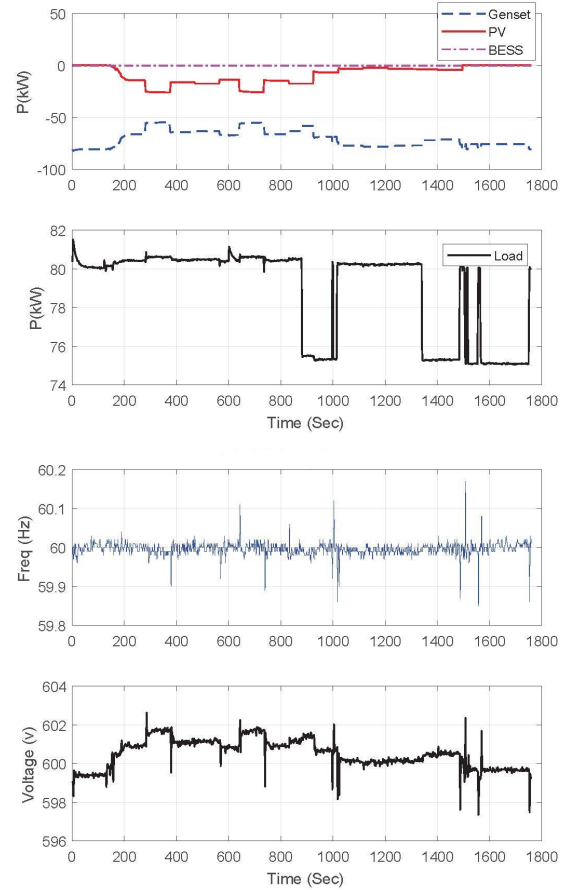


Fig. 5: Test A results.

case of the Fort Severn project Phase I in Northern Ontario with roof-top solar PV systems in an isolated microgrid [5].

In this case, since the renewable penetration level is relatively low compared to the load, energy storage is not required. The diesel generator, load bank 1, PV simulator and PV inverters were connected to the microgrid bus. The PV system was in MPPT control mode, and the diesel generator was in isochronous mode. Fig. 5 depicts the active power of the diesel generator, PV system, and load, as well as the system voltage and frequency over a 30-minute period. The diesel generator is the only grid-forming asset in this case. Since there are no large step changes in the load and PV, the diesel generator can regulate the frequency and voltage within the allowable range. Note that if there is a large step change in the load, it can lead to system instability due to the low inertia of the system.

B. High Renewable Penetration

In the Test B, the diesel generator, load bank, PV simulator, wind simulator, and BESS were connected to the microgrid bus. The PV system was in MPPT mode, the diesel generator was in isochronous mode, the wind simulator was in PQ mode, and the BESS was in droop mode. The EMS in isolated mode was enabled to coordinate the DERs and BESS, achieving high renewable energy penetration while maintaining system stability. The objective of the test was to demonstrate the performance of the control system in the high renewable energy penetration levels.

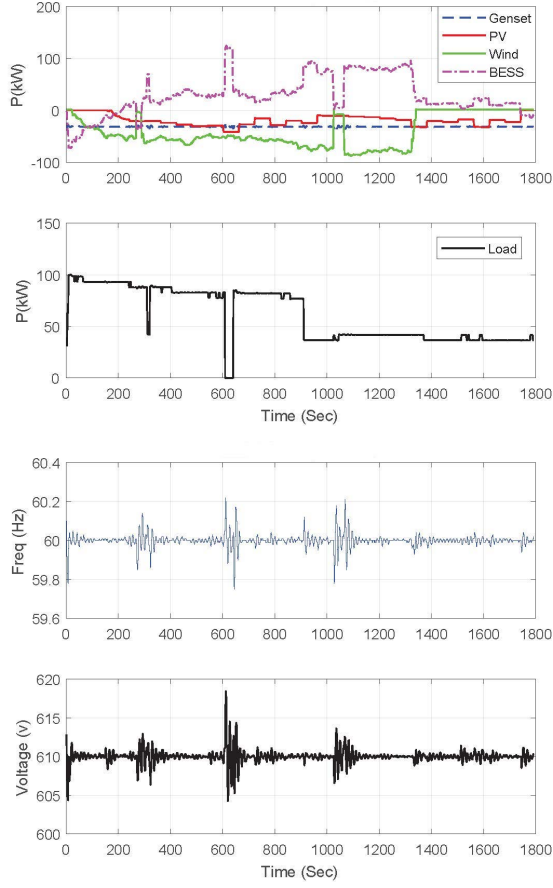


Fig. 6: Test B results.

Fig. 6 shows the active power of the diesel generator, PV, wind, BESS, and load, as well as the system voltage and frequency over a 30-minute period. The load profile included three short-term and long-term step changes to assess the control system performance. The first step change is a 50% drop with 10 s duration; the second step change is a 100% drop with 32 s duration to show the temporarily disconnection of the load with the longer duration; and the last step change is a 50% drop with 900 sec duration. The EMS defines the active power of the diesel generator at the minimum level in PQ mode (i.e., 30 kW). Since the diesel generator is in PQ mode to supply the base load, the BESS regulates the system frequency in droop mode; however, due to the presence of the diesel generator, the system frequency has some fluctuations, as illustrated in Fig. 6. The frequency of the system is maintained within the allowable range of IEEE 1547.4 [23], showing the effectiveness of the MCS and the BESS, regulating the frequency in isolated mode. It is worth mentioning that there are other configurations, which allow the diesel generator to be turned off.

C. 100% Renewable Penetration

The objective of the Test C was to demonstrate the performance of the control system with 100% renewable penetration. The test plan to achieve this objective was to apply the load profile with three step changes, as described in the previous section, and then apply the PV and wind simulators with the maximum power of 45 kW and 92 kW, respectively, using

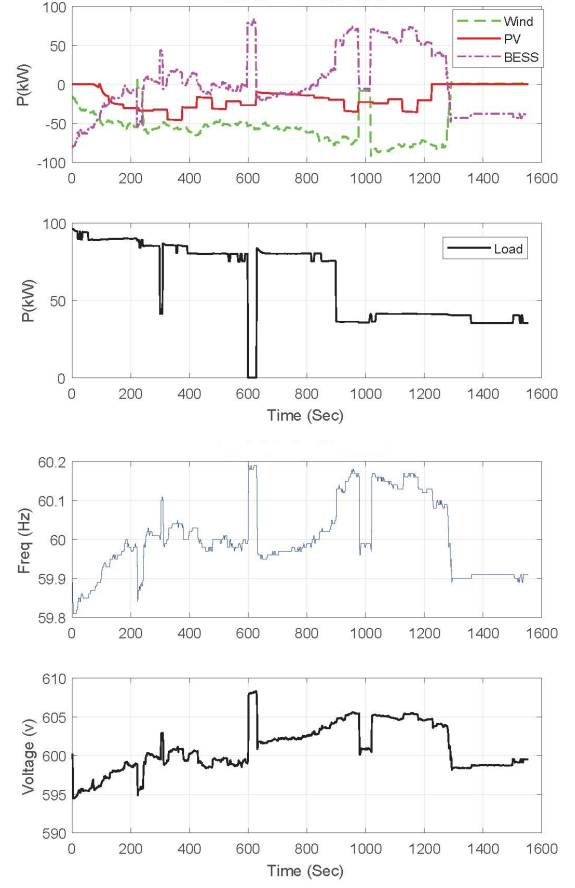


Fig. 7: Test C results.

pre-loaded profiles. The BESS energized the microgrid bus and stabilized the voltage and frequency as the grid-forming unit, and other assets were synchronized to the microgrid bus. In this case, the PV system was in MPPT mode, the wind simulator was in PQ mode, and the BESS was in droop mode.

Fig. 7 depicts the active power for the wind simulator, PV simulator, BESS, and load, as well as the system voltage and frequency over a 30-minute period. Note that the BESS adjusts the output power in order to regulate the frequency and the voltage within the allowable range, despite the step changes in the load and the intermittency of the PV and wind generators. Since the BESS was in droop mode, the steady-state values of the frequency was not 60 Hz all the time; however, the secondary controller ensured that the system power quality and stability requirements were met.

D. Mode Transition

The mode transition tests were designed to demonstrate the ability of the microgrid to perform the transition from grid-connected mode to islanded mode intentionally or unintentionally; these tests were performed using the grid through CB301 or the grid simulator through C205, with various configurations and subsets of the DERs. In this section, the transition from grid-connected to islanded mode is presented. In Test D, CB301 was closed and the microgrid was in grid-connected mode. The BESS was connected to the microgrid bus, injecting 25 kW to the grid.

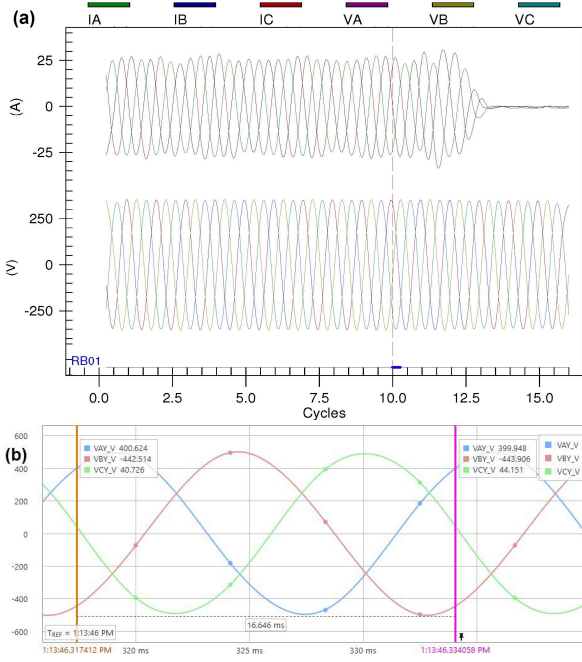


Fig. 8: Test D results: (a) Voltage and current at CB301. (b) Voltage at CB301 after transition.

Fig. 8 depicts the voltage and current waveforms at the CB301 during the transition. The breaker CB301 was triggered at 10 cycles, resulting in opening of the breaker at 13 cycles. The BESS controlled the transition with little voltage and frequency disruption. The voltage did not drop during the transition and the frequency slightly increased to 60.07 Hz after the transition. The voltage at the microgrid bus was stable and the transition was accomplished within the allowable tolerances. In the test shown here, other DERs are not connected to the microgrid bus, but other tests were performed with the combination of the DERs, demonstrating that the transition would not lead to the disconnection of other DERs, and resulted in seamless transfer from grid-connected mode to islanded mode.

VI. CONCLUSIONS

The CANREL was introduced in this paper, incorporating with the DERs, simulators, and energy storage system. Various operating modes such as islanded, grid-connected utilizing the grid simulator, utility grid-connected, and transition modes were described, and the hierarchical-based MCS approach to control and manage the microgrid assets of CANREL were presented. Some application examples for the benefit of the microgrid technical community were carried out, and some voltage, frequency, and mode transition tests were performed. The experimental performance tests and results presented in this paper demonstrate the system performance and the flexibility of the control system. These and other tests show that CANREL can be a powerful testbed for testing and deployment of renewable energy in the context of microgrids. CANREL is open for public collaboration with industry, government, and academia for the following:

- Testing of proponent-specific devices and products and controllers.

- Testing and demonstration of microgrids with high renewable penetration in islanded and grid-connected microgrids.
- Development of microgrid standards.

REFERENCES

- [1] E. Nasr-Azadani, C. Canizares, D. Olivares, and K. Bhattacharya, "Stability analysis of unbalanced distribution systems with synchronous machine and DFIG based distributed generators," *IEEE Trans. Smart Grid*, vol. 5, pp. 2326–2338, Sept 2014.
- [2] M. A. Nasr and E. Nasr-Azadani, "System performance in microgrids based hybrid pv systems," in *Proc. IEEE PES General Meeting*, Jul 2017.
- [3] E. Nasr-Azadani, C. Canizares, and K. Bhattacharya, "Modeling and stability analysis of distributed generation," in *Proc. IEEE PES General Meeting*, Jul 2012.
- [4] M. Arriaga, C. Canizares, and M. Kazerani, "Renewable energy alternatives for remote communities in northern ontario, canada," *IEEE Trans. Sustainable Energy*, vol. 4, pp. 661–670, July 2013.
- [5] M. Arriaga, E. Nasr-Azadani, and H. Rutherford, "Renewable energy microgrids in northern remote communities," *IEEE Potentials*, vol. 36, pp. 22–29, Sept 2017.
- [6] "National renewable energy laboratory, 2018, <https://www.nrel.gov/>."
- [7] R. H. Lasseter, J. H. Eto, B. Schenkman, J. Stevens, H. Vollkommer, D. Klapp, E. Linton, H. Hurtado, and J. Roy, "CERTS microgrid laboratory test bed," *IEEE Trans. on Power Delivery*, vol. 26, pp. 325–332, Jan. 2011.
- [8] "Power Systems Integration Lab, Alaska Center for Energy and Power, 2017, <http://acep.uaf.edu/facilities/power-systems-integration-lab.aspx>."
- [9] "Idaho National Laboratory: Microgrid Test bed, 2018, <https://renewableenergy.inl.gov/sitepages/home.aspx>."
- [10] E. Hossain, E. Kabalci, R. Bayindir, and R. Perez, "Microgrid testbeds around the world: State of art," *Energy Conversion and Management*, vol. 86, pp. 132–153, Oct 2014.
- [11] M. Barnes, A. Dimeas, A. Engler, C. Fitzer, N. Hatziaargyriou, C. Jones, S. Papathanassiou, and M. Vandenbergh, "Microgrid laboratory facilities," in *Int. Conf. Future Power Syst.*, Nov 2005.
- [12] G. Turner, J. P. Kelley, C. L. Storm, D. A. Wetz, and W.-J. Lee, "Design and active control of a microgrid testbed," *IEEE Trans. Smart Grid*, vol. 6, pp. 73–81, Jan 2015.
- [13] A. Cagnano, E. D. Tuglie, and L. Cicognani, "Prince—electrical energy systems lab: a pilot project for smart microgrids," *Electric Power Systems Research*, vol. 148, pp. 10–17, July 2017.
- [14] C. Wang, X. Yang, Z. Wu, Y. Che, L. Guo, S. Zhang, and Y. Liu, "A highly integrated and reconfigurable microgrid testbed with hybrid distributed energy sources," *IEEE Trans. Smart Grid*, vol. 7, pp. 451–459, Jan 2016.
- [15] M. Meiqin, D. Ming, S. Jianhui, L. Chang, S. Min, and Z. Guorong, "Testbed for microgrid with multi-energy generators," in *Canadian Conference on Electrical and Computer Engineering*, May 2008.
- [16] B. Zhao, X. Zhang, and J. Chen, "Integrated microgrid laboratory system," *IEEE Trans. Power System*, vol. 27, pp. 2175–2185, Nov 2012.
- [17] "European Distributed Energy Resources Laboratories, 2018, <http://www.der-lab.net/>."
- [18] M. Pereira, D. Limon, D. M. de la Pena, T. Alamo, and L. Valverde, "Periodic economic control of a non-isolated microgrid," *IEEE Trans. Industrial Electronics*, vol. 62, pp. 5247–5255, Aug 2015.
- [19] M. Petrollese, L. Valverde, D. Cocco, G. Cau, and J. Guerra, "Real-time integration of optimal generation scheduling with MPC for the energy management of a renewable hydrogen-based microgrid," *Applied Energy*, vol. 166, pp. 96–106, March 2016.
- [20] "IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems," in *IEEE Std. 1547.1*, 2005.
- [21] "Standard for inverters, converters, controllers and interconnection system equipment for use with distributed energy resources," in *UL 1741 Std*, 2010.
- [22] D. Olivares, A. Mehrizi-Sani, A. Etamadi, C. Canizares, R. Iravani, M. Kazerani, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G. Jimenez-Estevéz, and N. Hatziaargyriou, "Trends in microgrid control," *IEEE Trans. on Smart Grid*, vol. 26, pp. 1905–1919, May 2014.
- [23] "IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems," in *IEEE Std. 1547.4*, 2011.