Banshee distribution network benchmark and prototyping platform for hardware-in-the-loop integration of microgrid and device controllers

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Abstract: This article provides a unique benchmark to integrate and systematically evaluate advanced functionalities of microgrid and downstream device controllers. The article describes Banshee, a real-life power distribution network. It also details a real-time controller hardware-in-the-loop (HIL) prototyping platform to test the responses of the controllers and verify decision-making algorithms. The benchmark aims to address power industry needs for a common basis to integrate and evaluate controllers for the overall microgrid, distributed energy resources (DERs), and protective devices. The test platform will accelerate microgrid deployment, enable standard compliance verification, and further develop and test controllers’ functionalities. These contributions will facilitate safe and economical demonstrations of the state-of-the-possible while verifying minimal impact to existing electrical infrastructure. All aspects of the benchmark and platform development including models, configuration files, and documentation are publicly available via the electric power HIL controls collaborative (EPHCc).

1 Introduction

Recent natural disasters proved that microgrids offer a flexible layer of grid resiliency and service continuity to critical assets. One example is the Enchanted Rock virtual power plant microgrid in Texas, which consists of multiple natural gas generators installed at commercial sites. During Hurricane Harvey, this microgrid maintained electric service to 21 convenience stores and gas stations in the Houston area, providing access to essential products and services [1]. Similarly, Thermal Energy Corp. combined heat and power (CHP) facilities continued to provide uninterrupted thermal energy services to Texas Medical Centre during the same storm [1]. Other successful microgrid experiences relate to Hurricane Sandy where Princeton University, New York University, and Co-op City in Bronx, New York, remained partially or fully in service after losing utility power [2]. Indeed, microgrids are effective solutions to interconnect distributed energy resources (DERs), storage assets, and loads to increase service continuity and improve operational efficiency. Details on the most important aspects of AC and DC microgrids are given in [3, 4].

Microgrid systems are challenging and expensive to design, deploy, test, and maintain. The lack of appropriate engineering tools, industry standards, and field experience to develop, operate, and assess microgrids and DER control technologies damps the enthusiasm for adaptation by utility companies. Similarly, the limited prototyping capabilities of equipment vendors and system integrators to demonstrate their design and control solutions raise concerns for marketing ‘vapourware’ as well as a perceived risk by project developers and investors.

Furthermore, the power systems industry is not have openly available, well-adopted benchmarks adequate to test features or interoperability of microgrid and DER controllers, especially for networked power systems. Although helpful, IEEE test feeders, International Council on Large Electric Systems (CIGRE) benchmarks [5, 6], and Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid [7] may not always be sufficient to rigorously test control functionalities that involve reconfiguration of networked distribution circuits, management of microgrids with multiple points of coupling to utility service feeds, and synchronisation of multiple energised areas, among other features. The current approach to integrate and test controllers pushes project development risk to the final commissioning stage where equipment is deployed in the field, rather than reducing integration risk through staged testing and verification during the design process using low-cost prototyping.

Fortunately, IEEE standards 2030.7 [8] and 2030.8 [9] to specify and evaluate microgrid controllers are now available. The IEEE standard 1547 [10] for the interconnection and interoperability of DERs was revised, largely favouring microgrids. Real-time simulation technologies capable of interfacing system

J. Eng., 2019, Vol. 2019 Iss. 8, pp. 5365-5373
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emulators with hardware devices facilitate development of power systems prototyping platforms to systematically assess control functionalities of vendors’ product lines [11, 12]. The power industry recognises real-time hardware-in-the-loop (HIL) as a viable and cost-effective method to design, test, and precommission microgrids. Finally, several publications and reports support HIL testing for DER-related studies [13–19].

This paper contributes a real-life, reconfigurable test feeder (hereafter referred to as ‘Banshee”). It presents challenges typically found in a community microgrid, small island, and industrial facility. Banshee resembles emerging microgrids around the world, making it a comprehensive benchmark to evaluate microgrid performance. Presently, industry leaders use the system to demonstrate advanced controls and functionalities [20–22]; the National Renewable Energy Laboratory (NREL) used Banshee to benchmark its competitive procurement of microgrid controllers [23]; and universities are using Banshee to develop control algorithms and analysis tools [24]. Other contributions include design details for the real-time power system HIL Laboratory Testbed and Open Platform (HILLTOP).

The source code, stimuli profiles, component unit tests, and circuit designs for HILLTOP are publicly available as open-source code in the electric power HIL controls collaborative (EPHCC) repository [25].

2 Technology testing platform

The attractive trade-off between low cost, test fidelity, and excellent test coverage of controller HIL (CHIL) led to the development of HILLTOP to solve technical integration issues between controllers at different levels of decision-making and system operation.

2.1 Reasons for integration and testing of microgrid and device controllers with a CHIL-oriented approach

Microgrid and DER controllers vary extensively from vendor to vendor in capabilities, maturity levels, and project-specific integration work. Possible incompatibilities and lack of standardised integration procedures raise concerns for engineers and project developers. HILLTOP helps to evaluate the gamut of system conditions, guides debugging of control algorithms, demonstrates controllers’ marketed capabilities, and supports revision of electrical feasibility. Thus, microgrid adoption can significantly accelerate by facilitating realistic demonstrations, enabling risk-reduction testing, and pre-commissioning system integration and testing. Additionally, HILLTOP could help substantiate microgrid operations and corresponding controllers’ performance in compliance with IEEE standards [8–10].

2.1.1 Technical challenges to the widespread deployment of microgrid architectures: The main technical challenge to the widespread deployment of microgrids is the integration and interoperability between microgrid controllers and controllers of downstream devices. The power industry has identified numerous issues as impediments to microgrid deployment:

- High non-recurring engineering cost because of the project-specific integration and interoperability testing.
- Product vapourware, where advertised functionalities are neither available nor vetted for field implementation.
- High risk of damage to expensive equipment during deployment and integration testing.
- Cyberphysical concerns about microgrid and device controller malfunctions leading to equipment damage.
- Uncharacterised behaviour of proprietary control software and the unknown response to a specific power system.
- Lack of suitable analysis tools for utility engineers to properly quantify the dynamic behaviour of new assets and control systems in response to utility daily operations.
- Absence of methods to evaluate microgrid controllers compliance against industry standards. Recently, the IEEE published standards related to microgrids [8, 9]; however, distribution utilities consider their own specific regulations. Unfortunately, there are no standard cost-effective methods to test microgrid designs against upcoming standards or defined requirements by project developers and end users.

A standardised technology platform and benchmark system to integrate microgrid and DER controllers will help address existing concerns by facilitating design, device integration, interoperability evaluation, pre-commissioning testing, and standards compliance testing of microgrids and respective components. The industry needs software development and integration work completed and demonstrated well ahead of construction. This will reduce technical, safety, and financial risk perceived by utility engineers and project developers, possibly resulting in a higher approval rate of projects. Furthermore, a test platform will encourage DER and microgrid controller vendors to bring their products to maturity and prove their capabilities in terms of competitiveness and integration and testing challenges introduced by microgrid systems, HILLTOP focuses on microgrid controllers and the assets they integrate.

2.1.2 CHIL-oriented approach to microgrid integration testing platforms: Microgrids and similar advanced power system testbeds can be generally ranked based on characteristics such as overall cost, test fidelity, and test coverage (see Fig. 1). First, testbed costs include assembly, development, operation, and maintenance. Second, the achievable test fidelity is a decisive criterion where emulated behaviour on the testbed must be accurate enough to match the behaviour exhibited by the final deployed microgrid. Finally, high importance is given to the available test coverage and reproducibility of results. The testbed must be capable of simulating potentially dangerous or damaging ‘edge conditions’ without risking test equipment or personnel safety while producing reliable results.

Software-only simulations are at the low-cost, low-fidelity, high-test-coverage end of the spectrum. This approach enables evaluating a full range of test conditions. However, software simulations usually do not incorporate actual DER control behaviour because the proprietary software and firmware implemented by vendors for DER controls is rarely available for inclusion in the model. At the opposite end of the spectrum are actual, fully built, full-power, and operational microgrids, providing the highest test fidelity, but at a high cost and limited test coverage due to the risk of damage to expensive components. Power testbeds incorporate scaled-down DER components or test single components while neglecting system-level interactions. Both methods provide some cost relief at the expense of test fidelity. Power HIL (PHIL) testbeds commonly test a single DER, typically a solar inverter or battery inverter, by interfacing the DER under test with power amplifiers and simulating the behaviour of the remaining power system. PHIL provides realistic environment for testing DERs [26, 27] NREL Energy Systems Integration Facility (ESIF) [28], Clemson University SCE&G Energy

Fig. 1 Notional trade-off between test coverage and test fidelity for design concepts of microgrid prototyping testbeds. Shaded areas are qualitative and indicate overlap of test features between design concepts.
Innovation Centre [29], Florida State University (FSU) Centre for Advanced Power Systems (CAPS) [30], and the Austrian Institute of Technology (AIT) SmartEST Laboratory [31] are examples of these types of testbeds.

CHIL testbeds simulate, in real time, the expensive, potentially dangerous, high-power high-voltage equipment such as inverters, generators, loads, circuit breakers, energy storage, and transformers. Unlike software-only simulations, CHIL physically interfaces real controller hardware to operate virtual power components [32]. Controllers use proprietory algorithms and configurations, as they do in the field, to operate DER, protection devices, and distribution equipment. This approach provides a high-fidelity system behaviour while testing a wide range of operating conditions and risk-free switching sequences to real equipment. The primary challenge with CHIL is the development of validated power equipment models. EPHCC alleviates this difficulty as research entities, component manufacturers, and controller vendors can contribute characterised, certified, or validated models of their products to further improve industry standards and accelerate microgrid deployments.

2.2 Platform setup and integrated components

Banshee’s layout and designated test sequence heavily influenced the selection of hardware controllers for HILLTOP. Fig. 2 shows the testbed architecture and its physical components. Layer 1 represents the distribution management system (DMS), market signal source, forecasting engine, and microgrid controller, all communicating using Modbus® TCP or IEC 61850 messaging via a firewall in Layer 2. Layer 2 shows the cyber aspect of the platform including a firewall to manage communications traffic, a command and control proxy to facilitate man-in-the-middle attacks, and various Ethernet gateways to enable translation from Serial or Controller Area Network (CAN) bus into Modbus TCP.

Layer 3 consists of commercial device controllers. There are two genset controllers to control a diesel generator and a natural gas-fired CHP plant. Two power electronics controllers operate a battery energy storage system (BESS) and a photovoltaic (PV) system. Three feeder protection relays actuate circuit breakers at the points of coupling with the utility. A discrete programmable automation controller (DPAC) performs fast load shedding and fast configuration monitoring.

Layer 4 denotes custom-made interface circuitry to close the control loop between simulated equipment and their corresponding hardware controllers through scaling and mapping of generated signals. Layer 5 represents the test feeder and micogrid components implemented in a digital real-time simulator (DRTS).

In addition to device integration testing, the CHIL platform includes integration with a simplified supervisory DMS following user instructions or test sequence. The DMS instructs the microgrid controller to adjust optimisation objectives through commands such as import limits, export request, power factor correction, and disconnect requests.

2.3 Controller interface circuitry

To ensure proper operation, device controllers have specific ranges for input and output signals typically defined by the manufacturer. Similarly, the inputs and outputs channels of real-time simulators are hardware-limited. If the terminal signals between device controller and simulator do not match operation ranges, an interface circuit may be required to close the communications loop between the hardware and simulators.

The interface circuit can be built into the device controller, leveraging its circuitry to map and condition simulator signals. This method is relatively easy and inexpensive; however, it voids manufacturers’ warranty, tampering with intellectual property, and possibly reduces trust in the testbed setup. Fig. 3 illustrates the preferred approach for HILLTOP. The example shows the interface between the simulated diesel generator with a controller. This preferred method involves more manual labour and development risk, but the controller remains an off-the-shelf ‘black box’ and mimics field installations.

Fig. 3 shows the voltages and currents at the genset and feeder terminals mapped to the interface circuit. The interface provides signal conditioning to match the real-time simulator outputs to the controller input ranges using potential transformers, current transformers, and passive electronics for internal protection. Often, it is possible to apply digital signal scaling to reduce circuit complexity while complying with the simulator hardware limits. The device controller receives processed signals along with external power request commands that allow it to implement proprietary algorithms to produce the governor and automatic voltage regulator (AVR) bias signals to drive the simulated generators as it would for actual machines.

The feeder protection relays communicate with the simulator using built-in low-energy analogue voltage inputs as potential transformers and operational transconductance amplifiers as current transformers. The digital interfaces controlling breaker actions and monitoring status directly connect to mechanical contacts within the relay. The relays observe in real time the simulated voltage and currents, and similar to field implementations, the relays operate according to programmed functionalities and system conditions.

Other controllers operate using signals within ranges of the simulator’s input/output capabilities and require minimal interface circuitry. For example, the inverter boards, driving the insulated-gate bipolar transistor (IGBT) bridge in the PV inverter and storage inverter, have direct connections to the real-time simulator for analogue and digital channels. Similarly, the DPAC interfaces to the simulation platform via custom level-shifters and signal conditioning hardware. Detailed information about the design and construction of the interface circuitry for the genset controllers, protective relays, DPAC, and inverter boards are provided in the EPHCC repository [25].
2.4 Platform timescales and operation ranges

Across various industries, real-time simulations facilitate the design and evaluation of control systems and protection schemes. To demonstrate a microgrid’s electrical feasibility, the dynamics of interest range from 1 hertz to 5 kilohertz; covering system faults, switching transients, power converter response, protection actions, load dynamics, and mechanical changes. Fig. 4 illustrates typical timescales for power distribution system operations showing slower dynamics on the right side and faster responses on the left side [33, 34].

To maintain numerical stability while solving microgrid dynamics such as synchronisation or response to faults, simulation time steps of 100 ms or less are commonly required. Note that power flow studies fall within the slow simulation timescale and cannot explore transients, device controller responses, or fast-dynamics such as synchronisation or response to faults, simulation results. HILLTOP simulates Banshee well over the Nyquist criterion for the highest frequency of interest, typically nearly four times the highest frequency component of faults, switching transients, and device control responses.

3 Benchmark modelling approach

3.1 Network

3.1.1 Banshee distribution network topology: The Banshee distribution system is a real-life, reconfigurable, small industrial facility serviced by three non-dedicated utility radial feeders. Appendix 1 shows the system layout and its components. The model presents typical microgrid challenges seen around the world in community microgrids, small islands, and industrial facilities. Banshee consists of three adjacent feeders with limited connectivity through normally open switches, each capable of carrying the site's critical load. The overall electrical demand of the system ranges from 5 to 14 megawatts for the minimum and maximum loads. The system ratings include medium voltages of 13.8 and 4.16 kilovolts, and low voltages of 480 and 208 volts. There are 18 aggregated loads continuously supplied by the feeders. These loads are categorised as critical, priority, and interruptible. Table 1 provides a summary of all elements in the system.

The loads follow time-varying electrical demand profiles extracted from smart metering equipment installed at the existing buildings. Furthermore, there are two large induction motors rated 200 horsepower with compressor loads, one of the largest sizes recommended by the National Electrical Code (NEC) for line voltage start-up [35]. Critical loads highlight strict requirements of continuous electrical service, power quality, and reliability. Priority loads are buildings that are ideally always electrically served, but in the case of contingencies or islanding operations with lack of generation reserve, the loads may be disconnected. Interruptible loads are buildings not necessarily required during contingencies or islanded conditions. Providing a weight of importance to the loads facilitates the evaluation of microgrid controllers and their functionalities.

Rotating generation assets consists of a 4,000-kilowatt-ampere diesel generator and a 3,500-kilowatt-ampere, natural gas-fired CHP system operating at 13.8 kilovolts. The genset controllers operate and protect these units. The configurations of the controllers match the engine types of diesel and natural gas-fired generators. These controllers operate using voltage and frequency (V/F) droop control with 4% linear droop. These controllers receive dispatch set-point commands from the microgrid controllers without operator intervention.

Banshee includes a 3,000-kilowatt PV array and a 2,500-kilowatt-ampere BESS. Two inverter module controllers capable of four-quadrant operations and grid-mode transition techniques operate these assets. The PV follows a time-varying irradiance profile that matches a predefined test sequence. The microgrid controller fully operates the BESS for power factor correction, peak shaving and smoothing, and possibly power export. Although the actual site does not have all the DERs shown in Appendix 1, future expansion may include installation of renewable energy sources and storage facilities depending on economic incentives. However, this present lack of generation and storage in Banshee facilitates the evaluation of the microgrid controller's ability to perform smart load shedding prior and during islanded conditions.

Banshee is reconfigurable via a number of circuit breakers that also act as load-shedding disconnects. Microgrid controllers can interface and command these breakers via hardware or simulated relays. However, circuit breakers for the diesel generator and natural gas CHP solely actuate via the embedded logic of the genset controller.

Three hardware feeder protection relays monitor the point of interconnection (POI) between Banshee and the utility grid. Virtual relays provide protection against internal system faults and facilitate telemetry to the microgrid controllers. Protection elements include synchronism check, phase instantaneous overcurrent, AC inverse-time overcurrent, phase undervoltage, and phase overvoltage.

Banshee could be adopted to evaluate various microgrid controller functionalities including algorithms for dispatch operations and asset coordination, demand response via load

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**Table 1: Elements of the banshee network**

| Symbol Description                                      | Symbol Quantity |
|---------------------------------------------------------|-----------------|
| feeder protection relays                                | 3               |
| power inverter controllers                              | 2               |
| motor/generator controllers                              | 2               |
| diesel generator                                        | 1               |
| CHP generator                                           | 1               |
| PV system                                               | 1               |
| BESS                                                    | 1               |
| distribution transformer                                | 22              |
| medium- and low-voltage line (>500 ft)                  | 19              |
| induction motors with compressor loads                  | 2               |
| low-voltage loads                                       | 18              |
| circuit breakers                                        | 55              |
| virtual protective relays                               | 50              |

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management and curtailment, controller response to planned and unplanned disconnections from the utility service, reconfiguration of networked circuits, system blackstart, management of multiple points of coupling with the utility service, active resynchronisation of multiple islands, among other functionalities defined in IEEE 2030.7 [8].

3.1.2 Feeders, secondary main, and distribution transformer model: Three-phase series resistive-inductive branches with mutual inductances represent medium-voltage conductors and secondary mains. Branch parameters are computed using cable lengths extracted from the site one-line diagram and typical impedance data available in [36].

The distribution transformer operates with fixed-turn ratios and consists of three single-phase transformers connected in delta-wye-grounded configuration with negative 30 degrees angular displacement. The single-phase transformers are linear with magnetising branches represented by constant per-unit values of resistance and inductance; future work may include modelling of non-linear magnetising branches. Appendix 1 shows the site one-line diagram including transformer ratings, voltages, winding impedances, and X/R ratios.

3.1.3 Utility grid model parametrisation: Typically, at least two substations would energise a distribution system resembling Banshee's architecture. As of a lack of utility power system data, a single substation represents the upstream service. The substation configuration includes two 50-megavolt-ampere transformers energised by a 115-kilovolt Thevenin source, two busbars with normally open ties, four non-dedicated medium-voltage feeders, and feeder circuit breakers (items not shown in Appendix 1). Each feeder matches the available utility short-circuit contribution at the points of common coupling (see Appendix 2 – Table 2), which facilitates steady-state power flow and coordination studies.

3.2 Components

3.2.1 Circuit breaker and protective relay model: The circuit breakers are represented as controlled three-phase switches with integrated measurement probes acting as ideal potential transformers and current transformers, each with an individually predefined mechanical delay for open and close operations. Virtual or hardware relays use measured values of phase currents and terminal voltages to compute trip conditions. Once trip conditions are satisfied or the microgrid controller requests the circuit breaker to open, a disconnect command is issued to the breaker causing switches of each phase to open at their current zero crossing.

The relay model emulates commonly used protection elements such as instantaneous overcurrent, AC inverse-time overcurrent, undervoltage, overvoltage, and synchronism check. Similar to commercial units, the model facilitates system telemetry, circuit breaker operations for load shedding or reconfiguration, and multiple protection group settings. External controllers may actuate the relays via Modbus TCP using dedicated IP addresses.

Protection elements determine trip conditions by comparing over time the simulated voltage and current signals against minimum pickup values obtained from coordination studies. The trip command augments the logic of all protection elements in the relay and asserts to logical high when any of the elements is active. The synchronism check is available for dead-bus conditions and two energised circuit breaker terminals, where the voltage of one or both terminals is near zero without faults present in the circuit. The logic operates on a single-phase voltage using a Simulink built-in block to compute the true RMS by means of numerical integration over a sliding window, and a phase-locked loop (PLL) that tracks frequency and angle values. Once terminal voltages, slip frequency, and angle difference fall within appropriate settings, the synchronism check indicates that it is permissible to close the circuit breaker contacts.

3.2.2 Load model: Balanced three-phase time-varying current sinks simulate dynamic loads following real and reactive power profiles extracted from measurement equipment. Current sinks are calculated comparing simulated power consumed by the load against a demand profile, thus generating an error signal. This error drives a proportional integral derivative (PID) servo loop to generate current commands based on the compensation of real and reactive power differences (see Fig. 5). Real power corresponds to current flowing in phase with each phase voltage, and reactive power correlates with the current flowing in quadrature with each phase voltage. Thus, positive reactive power means there is current lagging voltage. A PLL generates a reference used for an abc-transformation. The active load operates on a time constant of 1 s, adequate to reproduce practical real-life load profiles.

3.2.3 Diesel generator model: The generator model consists of the numerical representation of a diesel engine (prime mover) and alternator (synchronous generator). The AVR controls the synchronous machine's field voltage, and the governor regulates the diesel engine's throttle to control frequency. A secondary-level generator controller, in this case a genset controller, adjusts the voltage and frequency set points. Two low-latency inner control loops regulate output voltage and frequency. Typically, manufacturers tune the low-level inner control loops for a variety of operating conditions to ensure stability and a quick response to perturbations. The tuning parameters are commonly unavailable to customers, and, therefore, the controller coefficients for the governor and AVR were determined by an iterative tuning process using as reference engineering considerations and field measurements of a similar size genset. The chosen controller parameters produce dynamic responses that are within accessible operating ranges for generator start-up, shutdown, and step load changes. Fig. 6 shows approximate capability curves for the generators in Banshee. The microgrid controller communicates power commands directly to the secondary-level controllers, which then implement mid-level control schemes such as frequency droop, voltage droop, synchronisation, and power quality refinements.
3.2.4 CHP model: The CHP model demonstrates the basic mechanism to supply or alleviate thermal demand using take-off heat from a natural gas generator engine, while serving electrical load. Additionally, the model shows microgrid controller features such as electrothermal co-optimisation. Similar to the diesel generator, a secondary-level genset controller adjusts set points for voltage and frequency according to power commands from the microgrid controller. Fig. 7 illustrates a high-level scheme of the CHP architecture and data flow.

The natural gas generator engine follows the approximate capability curve given in Fig. 6. The thermal loop considers a notional aggregation of a thermal mass that represents time-varying building heat load, a boiler that maintains temperature at a defined set point, and CHP heat that considers mixing and piping transport delays. The model assumes a heat exchanger can draw 20% of energy consumed by the engine to preheat the condensation return to the boiler. Unit testing shows the CHP plant temperature (Celsius) and heat behaviour while offloading the notional boiler as shown in Fig. 8. During the initial phase of heating, the temperature (red dashed line) rises while both the boiler (solid black line) and the CHP (dotted pink line) supply heat. The boiler regulates temperature (see Fig. 7), and the boiler heat is augmented by the CHP heat through the heat exchanger switch. When the temperature set point of 22 degrees C is reached, the boiler minor loop retracts to maintain constant temperature as shown by the steep negative slope of the boiler heat in Fig. 8. The engine incorporates response characteristics of a natural gas generator presented in [37] supported with validated dynamic data for a 350-horsepower machine. Details include valve assembly, throttle body, intake manifold, and engine block. The model parametrically scales to approximate displacement of the engine referring to [38].

3.2.5 Inverter model: The inverter models for the battery storage and PV system implement a vendor-verified power stage of a two-level, three-phase power inverter module. The inverter controllers use proprietary DSP-based inverter control boards directly interfaced with the real-time simulated inverter models. The controller outputs gate drive signals for the six-switch IGBT bridge as an input to the real-time simulator. The controller closes the loop with scaled analogue signals emulating the DC bus voltage and current of the inverter, the three-phase AC terminal voltages and currents, the module temperatures, and the three-phase AC grid voltage. Fig. 9 illustrates the inverter scheme.

Model fidelity is a function of many factors including simulation time step, real-time simulator latency, and digital sampling frequency. Latency refers to the maximum amount of time to read simulator inputs, compute the models' states, and produce signal outputs [33]. In general, faster time steps imply greater solution accuracy at the expense of computing resources. For HILLTOP, the inverter controller operates at a switching frequency of 5 kilohertz (200 μs). The Typhoon-HIL platform solves Banshee, including all of its components, at a 4-microsecond time step for the electrical system and 20-nanosecond digital sampling for the inverter controllers. This sampling facilitates detailed studies of switching harmonics and their influences on the system. Fig. 10 shows the inverter output currents before and after filtering for a 300-kilowatt step load during grid-forming mode. The zoomed-in overlay of the waveforms exemplifies the effect of the inverter switching frequency to the current injected into the grid.

The Opal-RT platform simulates Banshee, including all of its components, at a 4-microsecond time step for the electrical system and 20-nanosecond digital sampling for the inverter controllers. This sampling facilitates detailed studies of switching harmonics and their influences on the system. Fig. 10 shows the inverter output currents before and after filtering for a 300-kilowatt step load during grid-forming mode. The zoomed-in overlay of the waveforms exemplifies the effect of the inverter switching frequency to the current injected into the grid.

The Opal-RT platform simulates Banshee, including all of its components, with time steps between 25 and 100 ms. The simulator field-programmable gate array (FPGA) card samples the inverter gating signals at 10 ms. Interpolation methods and solvers couple the FPGA gating data to the main simulation using a digital time-stamping technique [39, 40]. The development focused on evaluating microgrid controllers' functions and capabilities. Although time steps of 100 ms reduce solution accuracy,
3.3 Model verification and simulation results

An important aspect of power system modelling for time domain simulations is to verify model correctness before performing studies and drawing conclusions. Component-level verification of dynamic performance and unit testing increases confidence in operations and responses to transient events. At the system level, steady-state verification ensures correct topology and overall system operations.

The steady-state verification of Banshee involved the comparison of phase currents and nodal voltages between five simulation tools. These tools include three real-time simulators that use high temporal accuracy time-domain solution methods Opal-RT, Typhoon HIL, and RTDS® and two well-known power flow software tools, the power system design and analysis tool from SKM and open-source simulator MATPOWER. The comparison considers normal operating conditions with open feeder ties, offline induction motors, offline generation assets, loads set to 100% of rated kilovolt-ampere at a power factor of 0.90 lagging, and total system load supplied by the utility feeds.

The results show voltages within acceptable operation ranges (see Fig. 11). To compare current flows between simulations, the average of the currents metered at each circuit breaker served as observation points (see Fig. 12). The results indicate agreement between models with maximum relative difference of 4.6% corresponding to an absolute difference of 0.4 amperes on a cable with 10 amperes of nominal current. The maximum absolute current difference is 22 amperes, introducing only 2.3% relative difference. These small discrepancies may be consequences of numerical implementations, inaccuracy of impedances, modelling approach, or differences in solution methods. However, for all practical purposes, these differences are negligible. Overall, the results show that different solution methods cross-confirm the validity of the model. Additionally, external verification using alternate software yielded similar comparison results.

Dynamic performance verification entails unit testing and overall model behaviour to selected system changes. This verification confirms the response of the device under test to be within practical bounds. For brevity, this paper only presents testing for the 4,000-kilovolt-ampere diesel generator using models implemented in the Opal-RT and Typhoon HIL platforms.

4 Conclusions and lessons learned

This paper presents Banshee, a real-life power system that serves as a microgrid and DER controller integration test system. Banshee supplements existing test feeders by providing the means to...
evaluate microgrid controller functionalities that involve reconfiguration of networked circuits, blackstart, management of multiple points of coupling with the utility service, active simulation and testing platform, where all related design documents and controllers' configuration files are publicly available in the EPHCC repository. The shown simulation cases confirm the value of the Banshee distribution network benchmark as a prototyping platform suitable for HIL integration of microgrid and device controllers.

5 Acknowledgments

This paper was produced as part of the IEEE Task Force on Real-Time Simulation of Power and Energy Systems. The authors would like to thank Will Allen of Schweitzer Engineering Laboratories, Vijay Bhavaraju and Quang Fu of Eaton, Thomas Steber of Schneider Electric, and Jayant Kumar of General Electric, for their participation in the Symposium for Integration and Testing of Microgrid and DER Controllers showcasing HILTOP to utility engineers and project developers. Special thanks to Kim Sarff of Schweitzer Engineering Laboratories for the professional editing of this work.

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited. This material is based upon work supported by the Department of Energy under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Department of Energy.

6 References

[1] Wood, E.: ‘Hurricane harvey creates new abnormal for the electric grid’, Microgrid Knowledge, August 2017. Available at https://microgridknowledge.com/microgrids-and-hurricane-harvey/, accessed May 2018

[2] Breidenberg, A.: ‘Could decentralized microgrids solve the extreme weather outage problem?’ (Thomas Publishing Co., New York, 2012). Available at http://news.thomasnet.com/imt/2012/11/12/could-decentralized-microgrids-solve-the-extreme-weather-outage-problem, accessed May 2018

[3] Degner, T., Dimeas, A., Engler, A., et al.: ‘Microgrids: architectures and control’ (Wiley-IEEE Press, Chichester, 2014)

[4] Strunz, K., Aboulé, H., Hsu, D.N.: ‘Status report for wind and solar power integration’, IEEE J. Emerging Sel. Topics Power Electron., 2014, 2, (1), pp. 115–126

[5] CIGRE Task Force TF C6.04.02: ‘TB 575-benchmark systems for network integration of renewable and distributed energy resources’, April 2014

[6] Papanastassiou, S., Hatziargyriou, N., Strunz, K.: ‘A benchmark low voltage microgrid network’. CIGRE Symp. on Power Systems with Dispersed Generation, Athens, Greece, April 2005

[7] Lasseret, R.H.: ‘Certs microgrid’, 2007 IEEE Int. Conf. on System of Systems Engineering, San Antonio, TX, April 2007, pp. 1–5

[8] IEEE 2030.7: ‘IEEE standard for specification of microgrid controllers’, 2017

[9] IEEE P2030.8: ‘IEEE standard for testing of microgrid controllers’, 2018

[10] IEEE P1547: ‘IEEE draft standard for interconnection and interoperability of distributed energy resources with associated electric power system interfaces’, 2018

[11] Guillaud, X., Faruque, O., Teninge, A., et al.: ‘Applications of real-time simulation technologies in power and energy systems’, IEEE Power Energy Technol. Syst. J., 2015, 2, (2), pp. 103–105

[12] Faruque, O., Strasser, T., Lauss, G., et al.: ‘Real-time simulation technologies for power systems design, testing, and analysis’, IEEE Power Energy Technol. Syst. J., 2015, 2, (2), pp. 63–73

[13] Kotsampopoulos, P., Lehfluss, F., Gao, J., et al.: ‘The limitations of digital simulation and the advantages of PHIL testing in studying distributed generation provision of ancillary services’, IEEE Trans. Ind. Electron., 2015, 62, (9), pp. 5092–5103

[14] Wang, J., Song, Y., Li, W., et al.: ‘Development of a universal platform for hardware-in-the-loop testing of microgrids’, IEEE Trans. Ind. Inf., 2014, 10, (4), pp. 2154–2165

[15] Karapanos, V., de Haan, S., Zweetloot, K.: ‘Real time simulation of a power system with VSG hardware in the loop’. IECON 2011 – 37th Annual Conf. on IEEE Industrial Electronics Society, Melbourne, Australia, November 2011

[16] Lauss, G., Lehfluss, F., Hletterie, B., et al.: ‘Examination of LV grid phenomena by means of PHIL testing’. IEC61400-21 – IEC 61400-21 Annual Conf. on IEEE Industrial Electronics Society, Montreal, October 2011

[17] Palminteri, B., Lundstrom, B., Chakraborty, S., et al.: ‘A power hardware-in-the-loop platform with remote distribution circuit cosimulation’, IEEE Trans. Ind. Electron., 2015, 62, (4), pp. 2236–2245

[18] Johnson, J., Ahlting, K., Brüdinger, R., et al.: ‘Design and evaluation of SunSpec-compliant smart grid controller with an automated hardware-in-the-loop testbed’, Technol. Economics Smart Grids Sustain. Energy, 2017, 2, (1), p. 10

[19] Ivanović, Z.R., Adrić, E.M., Vekić, M., et al.: ‘HIL evaluation of power flow control strategies for energy storage connected to smart grid under unbalanced conditions’, IEEE Trans. Power Energy, 2012, 27, (11), pp. 4699–4710

[20] Schweitzer Engineering Laboratories. Available at http://selinc.com, accessed May 2018

[21] EATON. Available at http://www.eaton.com, accessed May 2018

[22] Manson, S., Nayak, B., Allen, W.: ‘Robust microgrid control system for seamless transition between grid-tied and island operating modes’. 44th Annual Western Dist. Conf., Spokane, WA, October 2017

[23] National Renewable Energy Laboratory, Competitive Procurement for Microgrid Controller Technology. Available at https://www.nrel.gov/esif/webinar-competitive-procurement.html, accessed May 2018

[24] Ilic, M.: ‘Market integration between wholesale and retail markets’. IEEE Power and Energy Society General Meeting, Chicago, IL, July 2017

[25] Electric Power Hardware-in-the-loop Controls Collaborative. Available at https://github.com/HIL-ePCC/releases/download/BansheeBenchmark/Supporting.Data.for.Banshee.Benchmark.Paper.zip, accessed July 2018

[26] Lauss, G., Strunz, K.: ‘Multi-rate partitioning (MRP) interface for enhanced stability of power-hardware-in-the-loop real-time simulation’, IEEE Trans. Ind. Electron., 2019, 66, (1), pp. 595–605

[27] Steurer, M., Bogdan, F., Ren, W., et al.: ‘Controller and power hardware-in-loop methods for accelerating renewable energy integration’. Proc. of Power Engineering Society General Meeting 2007, Tampa, USA, 24–28 June 2007

[28] NREL, Energy Systems Integration Facility. Available at https://www.nrel.gov/esif/, accessed May 2018

[29] Clemson University, SCE&G Energy Innovation Center. Available at http://clemsonenergy.com/duke-energy-egrid/, accessed May 2018

[30] Florida State University, Center for Advanced Power Systems. Available at https://www.caps.fsu.edu/, accessed May 2018

[31] Austrian Institute of Technology, SmartEST Laboratory. Available at https://www.aist.ac.at/en/research-fields/smart-grids/laboratories, accessed May 2018

[32] Maniatopoulos, M., Lagos, D., Kotsampopoulos, P., et al.: ‘Combined control and power hardware-in-the-loop simulation for testing smart grid control algorithms’, IET Gener. Transm. Distrib., 2017, 11, (12), pp. 3099–3108

[33] Dutfau, C., Belanger, J.: ‘Real-time simulation of microgrids’, in Martinez-Velasco, J.A. (Ed.): ‘Transient analysis of power systems: techniques, tools and applications’, 1 (John Wiley & Sons, Chichester, 2013), pp. 72–97

[34] Wason, N., Arrillaga, J.: ‘Power systems electromagneto transients simulation’ (IET Press, London, 2007)

[35] NFPA 70: National Electrical Code (NEC) Handbook, 2017

[36] ‘IEEE recommended practice for electric power distribution for industrial plants’, 1993

[37] Gangopadhyay, A., Meckl, P.: ‘Modeling and validation of a lean burn natural gas engine’, J Dyn. Syst. Meas. Control, 1998, 120, (3), pp. 425–430

[38] Jenbacher Type 6 Technical Brochure. Available at https://www.gegower.com/gas/reciprocating-engines/jenbacher/type-6, accessed May 2018

[39] Dutfau, C., Belanger, J.: ‘A real-time simulator for doubly fed induction generator based wind turbine applications’. Proc. of IEEE 35th Power Electronics Specialists Conf., Aachen, Germany, June 2004

[40] Dutfau, C., Abourida, S., Belanger, J.: ‘Real-time simulation of electrical vehicle motor drives on a PC cluster’. Proc. of the 10th European Conf. on Power Electronics and Applications, Toulouse, France, September 2003

7 Appendix

7.1 Appendix 1: topology of the banshee distribution network

See Fig. 15

7.2 Appendix 2: modelling data for banshee distribution network (see EPHCC for complete dataset, component models, and communication parameters)

See Tables 2–9.
Fig. 15 Topology of banshee distribution network

### Table 2 Short-circuit contribution of banshee

| Feeder   | 3PH (A) | X/R | SLG (A) | X/R |
|----------|---------|-----|---------|-----|
| Feeder 1 | 14,580  | 4.6 | 10,570  | 0.9 |
| Feeder 2 | 15,730  | 7.9 | 10,240  | 2.6 |
| Feeder 3 | 14,580  | 4.6 | 10,570  | 0.9 |

### Table 3 Parameters of the diesel generator

| Parameter                  | Description                                      | Units  | Value |
|----------------------------|--------------------------------------------------|--------|-------|
| MVA                        | Rated MVA of machine                             | MVA    | 4     |
| Vbll                       | Rated rms line-to-line voltage                   | kV     | 13.8  |
| Hz                         | Base angular frequency                           | Hz     | 60    |
| H                          | Inertia constant                                 | MW-sec/MVA | 0.35 |
| D                          | Synchronous mechanical damping                   | pu     | 0     |
| XS1                        | Stator leakage reactance                         | pu     | 0.05  |
| XMD0                       | D-axis unsaturated magnet reactance              | pu     | 2.35  |
| X2D                        | D: field leakage reactance                       | pu     | 0.511 |
| X3D                        | D: damper leakage reactance                      | pu     | 3.738 |
| XMQ                        | Q-axis magnetising reactance                     | pu     | 1.72  |
| X2Q                        | 1st Q-axis damper leakage reactance              | pu     | 0.2392|
| X3Q                        | 2nd Q-axis damper leakage reactance              | pu     | 0.0942|
| RS1                        | Stator resistance                                | pu     | 0.008979|
| R2D                        | Field resistance                                 | seconds| 0.00206|
| R3D                        | Direct-axis damper resistance                    | seconds| 0.2826|
| R2Q                        | 1st Q-axis damper resistance                     | seconds| 0.2392|

### Table 4 Parameters of the speed governor for the diesel generator

| Parameter | Description          | Units | Value |
|-----------|----------------------|-------|-------|
| K         | Regulator gain       |       | 10    |
| Kp        | Proportional gain    |       | 1     |
| Kd        | Derivative gain      |       | 0.5   |
| T4        | Actuator time constants | seconds | 0.025 |
| T5        | Actuator time constants | seconds | 0.0009|
| T6        | Actuator time constants | seconds | 0.00574|
| Tmax      | Max torque limits    | pu     | 2.0   |
| Tmin      | Min torque limits    | pu     | 0     |
| Td        | Engine time delay    | seconds| 0.024 |

### Table 5 Parameters of the exciter for the diesel generator – IEEE type 1

| Parameter | Description                                      | Units  | Value |
|-----------|--------------------------------------------------|--------|-------|
| Tr        | Voltage transducer time constant                 | seconds| 0.002 |
| Ka        | Voltage regulator gain                           |        | 200   |
| Ta        | Voltage regulator time constant                  | seconds| 0.002 |
| Efmax     | Maximum control element output                   | pu     | 5     |
| Efmin     | Minimum control element output                   | pu     | 0     |
| Ke        | Exciter field resistance line slope margin      | pu     | 1     |
| Te        | Exciter field time constant                      | seconds| 0.0001|
| KF        | Rate feedback gain                               | pu     | 0     |
| Tf        | Rate feedback time constant                      | seconds| 0     |

### Table 6 Parameters of the natural gas CHP generator

| Parameter | Description                                      | Units  | Value |
|-----------|--------------------------------------------------|--------|-------|
| MVA       | Rated MVA of machine                             | MVA    | 3.5   |
| Vbll      | Rated rms line-to-line voltage                   | kV     | 13.8  |
| Hz        | Base angular frequency                           | Hz     | 60    |
| H         | Inertia constant                                 | MW-sec/MVA | 0.35 |
| D         | Synchronous mechanical                           | pu     | 0     |
| XS1       | Stator leakage reactance                         | pu     | 0.05  |
| XMD0      | D-axis unsaturated magnet reactance              | pu     | 2.35  |
| X2D       | D: field leakage reactance                       | pu     | 0.511 |
| X3D       | D: damper leakage reactance                      | pu     | 3.738 |
| XMQ       | Q-axis magnetising reactance                     | pu     | 1.72  |
| X2Q       | 1st Q-axis damper leakage reactance              | pu     | 0.2392|
| X3Q       | 2nd Q-axis damper leakage reactance              | pu     | 0.0942|
| RS1       | Stator resistance                                | pu     | 0.008979|
| R2D       | Field resistance                                 | seconds| 0.00206|
| R3D       | Direct-axis damper resistance                    | seconds| 0.2826|
| R2Q       | 1st Q-axis damper resistance                     | seconds| 0.2392|
### Table 7  Parameters of the exciter for the natural gas CHP generator – IEEE type 1

| Parameter | Description | Units | Value |
|-----------|-------------|-------|-------|
| Tr        | voltage transducer time constant | seconds | 0.002 |
| Ka        | voltage regulator gain | — | 200 |
| Ta        | voltage regulator time constant | seconds | 0.002 |
| Efmax     | maximum control element output | pu | 5 |
| Efmin     | minimum control element output | pu | 0 |
| Ke        | exciter field resistance line slope | pu | 1 |
| Te        | exciter field time constant | seconds | 0.0001 |
| Kf        | rate feedback gain | pu | 0 |
| Tf        | rate feedback time constant | seconds | 0 |

### Table 8  Parameters of the speed governor for the natural gas CHP generator

| Parameter | Description | Value |
|-----------|-------------|-------|
| cd        | discharge coefficient | 0.8 |
| H         | NG heating value | 47.133 |
| keq       | equivalent ratio of specific heats of air/fuel mixture | 1.3962 |
| Ma        | molecular weight of air | 0.029 |
| Meq       | equivalent molecular weight of air/fuel mixture | 0.0285 |
| Mf        | molecular weight of NG | 0.019 |
| P0        | throttle inlet air pressure | 800,000 |
| Pm        | intake manifold pressure | 37.241 |
| R         | universal gas constant | 8.314 |
| T0        | throttle inlet charge temperature | 300 |
| Tm        | intake manifold temperature | 325 |
| TE        | thermal efficiency | 0.45 |
| V         | manifold plus port passage volume | 0.031 |
| Vd        | engine displacement | 0.125 |
| VolEff    | volume efficiency | 0.9 |
| P         | proportional gain | 20 |
| I         | integral gain | 0 |
| UL        | upper limit | 1.05 |
| LL        | lower limit | 0 |
| UPL       | upper power limit | 5 |
| LPL       | lower power limit | –5 |

### Table 9  List of loads in banshee

| Load ID | Category | Feeder | kVA demand | Breaker for load shedding |
|---------|----------|--------|------------|----------------------------|
| C1      | critical | F1     | 1200       |                            |
| C2      | critical | F1     | 1500       |                            |
| C3      | critical | F2     | 1000       |                            |
| C4      | critical | F2     | 1000       |                            |
| C5      | critical | F3     | 1000       |                            |
| C6      | critical | F3     | 800        |                            |
| P1      | priority | F1     | 1200       | CB114                      |
| P2      | priority | F2     | 1000       | CB219                      |
| P3      | priority | F2     | 1000       | CB204                      |
| P4      | priority | F3     | 600        | CB307                      |
| P5      | priority | F2     | 700        | CB218                      |
| P6      | priority | F3     | 1000       | CB309                      |
| I1      | interruptible | F1 | 300 | CB104                     |
| I2      | interruptible | F1 | 250 | CB107                     |
| I3      | interruptible | F2 | 300 | CB206                     |
| I4      | interruptible | F2 | 600 | CB208                     |
| I5      | interruptible | F2 | 400 | CB212                     |
| I6      | interruptible | F3 | 600 | CB308                     |