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CERTS Microgrid Laboratory Test Bed*

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SUMMARY

The objective of the CERTS Microgrid Test Bed project was to enhance the ease of integrating energy sources into a microgrid. The project accomplished this objective by developing and demonstrating three advanced techniques, collectively referred to as the CERTS Microgrid concept, that significantly reduce the level of custom field engineering needed to operate microgrids consisting of generating sources less than 100kW. The techniques comprising the CERTS Microgrid concept are: 1) a method for effecting automatic and seamless transitions between grid-connected and islanded modes of operation, islanding the microgrid's load from a disturbance, thereby maintaining a higher level of service, without impacting the integrity of the utility's electrical power grid; 2) an approach to electrical protection within a limited source microgrid that does not depend on high fault currents; and 3) a method for microgrid control that achieves voltage and frequency stability under islanded conditions without requiring high-speed communications between sources.

These techniques were demonstrated at a full-scale test bed built near Columbus, Ohio and operated by American Electric Power. The testing fully confirmed earlier research that had been conducted initially through analytical simulations, then through laboratory emulations, and finally through factory acceptance testing of individual microgrid components. The islanding and resynchronization method met all Institute of Electrical and Electronics Engineers Standard 1547 and power quality requirements. The electrical protection system was able to distinguish between normal and faulted operation. The controls were found to be robust under all conditions, including difficult motor starts and high impedance faults.

The results from these tests are expected to lead to additional testing of enhancements to the basic techniques at the test bed to improve the business case for microgrid technologies, as well to field demonstrations involving microgrids that involve one or more of the CERTS Microgrid concepts. Future planned microgrid work involves unattended continuous operation of the microgrid for 30 to 60 days to determine how utility faults impact the operation of the microgrid and to gage the power quality and reliability improvements offered by microgrids.

KEYWORDS Field Experience, Laboratory and Test Results

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INTRODUCTION

Evolutionary changes in the regulatory and operational climate of traditional electric utilities and the emergence of smaller generating systems, including internal combustion engines, microturbines, photovoltaics, and fuel cells, have opened new opportunities for electricity users to generate power on site. In this context, distributed energy resources – small power generators typically located at sites where the energy (both electric and thermal) they generate is used – are a promising option to meet growing customer needs for economic and reliable electric power. The distributed energy resources portfolio includes not only generators but also energy storage and load control. Organizing all of these resources into microgrids is a promising way to capture smaller distributed energy resources' significant potential to meet customers' and utilities' needs.

Key features that will make microgrids functional, both within themselves and as elements of the larger electricity system, include high reliability so that customers receive the power quality they require, capacity for “plug and play” addition of energy resources to the microgrid so that placement of those resources is flexible, and operation of the microgrid so that it appears to the larger utility grid just like any other single customer site.

The Consortium for Electric Reliability Technology Solutions (CERTS) has developed a detailed Microgrid concept that aims to provide these and other technically challenging microgrid functionalities at much lower costs than traditional approaches to distributed energy resources by avoiding the need for extensive (i.e., expensive) custom engineering (Lasseter et al. 2002). This paper focuses on the creation of a full-scale test bed to demonstrate the CERTS microgrid techniques for providing reliable, high-quality power with no disruption to the electricity grid. We also briefly summarize testing performed to date and planned next steps.

THE CERTS MICROGRID CONCEPT

To achieve a high degree of functionality at reasonable cost, the CERTS Microgrid concept relies on peer-to-peer and plug-and-play strategies for each component within the microgrid.

The peer-to-peer concept insures that no single component, such as a master controller or a central storage unit, is required for operation of the microgrid. Therefore, by its very design, the CERTS Microgrid can continue operating with loss of an individual component or generator. With one additional source, (N+1) it can insure even higher levels of reliability.

The plug-and-play concept means that a distributed energy unit can be added or placed at any location within the microgrid without re-engineering the microgrid's controls. The plug-and-play functionality is similar to the flexibility one has with home appliances; just as an appliance can be plugged in wherever there is an outlet, a distributed energy resource within a microgrid can be located anywhere within a facility or building where it might be most needed. This is in sharp contrast to the traditional model for addressing distributed energy generation, which clusters distributed sources at a single point to simplify their electrical integration. In combined-heat-and-power applications, the plug-and-play model facilitates placement of distributed energy resources immediately adjacent to heat loads, thereby allowing most effective use of waste heat without a complex heat distribution system, e.g., steam and chilled water pipes, and the energy losses associated with them.

As noted above, another critical feature of the CERTS Microgrid is its presentation to the surrounding distribution grid as a single, self-controlled entity. A CERTS Microgrid appears to the grid as indistinguishable from any other customer site. This means that the microgrid avoids many of the current concerns associated with integrating distributed energy resources, such as how many of these resources the system can tolerate before their collective electrical impact begins to create problems like excessive current flows into faults and voltage fluctuations.

Among the critical functions a microgrid must perform are, when there is a utility grid disturbance, to separate and isolate (“island”) itself from the utility seamlessly with little or no disruption to microgrid loads (including no diminution of power quality during the transition). Both the loads and distributed generation located “downstream” of the static switch are thereby protected from the grid disturbance. Loads “upstream” of the static switch (yet still downstream of the point of common coupling with the utility grid) are exposed to the grid disturbance and are in this sense unprotected. When utility grid operations return to normal, the microgrid must automatically resynchronize and reconnect itself to the grid in an equally seamless fashion.

DEVELOPMENT OF THE CERTS-AMERICAN ELECTRIC POWER (AEP) MICROGRID TEST BED

The CERTS Microgrid concept is being demonstrated at the CERTS Microgrid-American Electric Power (AEP) test bed, located near Columbus, Ohio and operated by AEP (Eto, et al. 2008). See Figure 1. Northern Power Systems (NPS) designed the test bed (see Figure 2) and fabricated most of the major hardware elements, including load banks, power and control circuitry, protective relaying, and data-acquisition equipment, which are installed in metal-clad switchgear cabinets for protection in an outdoor location.

The four load banks of the test bed, Load-3 through Load-6 can be remotely controlled from 0-90 kilowatts (kW) and 0-45 kilovolt ampere reactive (kVar). Each bank also has remote fault loads which range from bolted faults to high-impedance faults (60 kW and 83 kW). Other loads include an induction motor 0-20 horsepower (HP). The digital acquisition system includes twelve 7650 ION meters providing detailed voltage and current waveforms for each phase conductor including the neutral.

Tecogen and its inverter manufacturer, Youtility, modified and factory-tested three combined-heat-and-power units to incorporate the CERTS Microgrid control algorithms. The complete systems each include an engine/generator, a “surge module” and an inverter. See Figure 3. Each inverter is sized to provide both 60 kW and ± 60 kVARS.

The prime mover for the engine/generator is a 454-cubic-inch displacement natural gas-fired V8 reciprocating engine. This engine was designed to be operated at a speed that gives the best combination of fuel efficiency and response to load changes. Thus, the engine speed will not necessarily be synchronous with a 60-Hertz (Hz) system. The electrical generator produces a variable alternating current (AC), which is rectified to a direct current (DC) output. The inverter converts the DC to utility-synchronous AC. The surge module is an energy storage device consisting of batteries, power electronics, and controls, which is tied to the DC bus in parallel with the electrical generator and the inverter. The purpose of the surge module is to provide instantaneous power when there is a load increase while the engine/generator adjusts its speed to the new loading conditions. The inverters and surge modules were both supplied to Tecogen by Youtility, Inc. Tecogen integrated the entire prime mover system and performed a set of factory acceptance tests, as specified by the CERTS team, before shipping the units to the test bed.

A critical aspect of this project was the incorporation of the CERTS Microgrid control algorithms into the inverters provided by Youtility. A set of test scenarios were performed prior to sending the inverters to Tecogen, to confirm correct operation of the completed inverters. Once at AEP’s facilities, the Tecogen units were retested to confirm that the performance of the installed units was consistent with the factory tests.

NPS designed, fabricated, and factory-tested a static switch that implemented CERTS Microgrid islanding and resynchronization procedures. The controls were implemented onto the static-switch hardware associated with a Purewave uninterruptible power supply system manufactured by S&C Electric. See Figure 4. The islanding procedures consisted of trip sensing [i.e., detect and trip on Institute of Electrical and Electronics Engineers (IEEE) 1547-specified criteria such as voltage or

frequency deviations and reverse power flow] followed by disconnection (islanding) of the microgrid from the utility. The voltage-trip function included trip-characteristics required by IEEE 1547 for distributed resource interconnection, those specified by the Information Technology Industry Council for power quality, and a custom-voltage-versus-time-trip characteristic that could be specified by the user.

The resynchronizing function had to meet a more stringent requirement than the commonly accepted criteria of IEEE 1547 to insure transient-free transitions for power flow either into or out of the microgrid at the instant of switch closing. IEEE 1547 requires that the phase difference across the switch be less than 20° before the switch can close. However, this phase difference is too large for microgrid needs, which require closing at a zero-phase difference. The high-speed static switch and digital signal processing insure that the voltage phase difference at closing is zero.

NPS tested the static switch with low-level power (i.e., signal injection) to confirm proper operation before shipping the switch to AEP. Technical Advisory Committee (TAC) members from the National Renewable Energy Laboratory shipped additional testing equipment and lent expertise to NPS in support of this testing. Once at AEP's facilities, the switch was retested with low power to confirm that there had been no shipping damage. AEP performed further testing at its Dolan Test Facility to examine selected power quality issues prior to installing equipment at the test bed.

NPS also fabricated cabinets containing all the sensing hardware for protection and data-acquisition equipment; the circuit breakers, switches and fuses; and all of the loads. The loads include a variety of resistive, inductive, capacitive and motor as loads well a six-pulse power rectifier to provide a non-linear load.

CERTS MICROGRID TESTS

Initial testing focused on:

- 1) a method for making automatic, seamless transitions between grid-connected and islanded modes of operation;
- 2) an approach to electrical protection within the microgrid that does not depend on high fault currents; and
- 3) a method for microgrid control that achieves voltage and frequency stability under islanded conditions without requiring high-speed communications.

AEP conducted five sets of tests.

The first set of tests examined the operation of the static switch to determine that it and its digital signal processing control operated as designed. This included five tests of dead-bus and synchronized closing, reverse power, and IEEE 1547 protective relay functions. The goal was to confirm the correct operation (and thus the protection) of the static switch, which is located at the interface between the protected (zones 3, 4, 5 in Figure 2) and unprotected (zone 6 in Figure 2) portions of the microgrid.

The second set of tests examined a preliminary set of faults (i.e., overload simulating a high-impedance fault) within the microgrid to ensure protection and safety of the test bed prior to performing other planned tests. The fault condition tests were intended to cover the basic concepts of the protection design and to study its effectiveness (e.g., zero-sequence, negative-sequence and residual currents for line-to-ground faults; negative-sequence or (I₂T) protection for phase-to-phase faults). For the majority of these test scenarios, the static switch was expected to open first, followed by the zone breaker of the faulted zone. The goal was to test and adjust protection settings to achieve the best conditions and protection design within a limited fault current system. Sixteen separate tests were conducted.

The third set of tests was designed to ensure that the Gen-set inverter controls were working as designed during grid-connected and islanded modes of operation. This includes unit control, zone control, and mixed power controls, in conjunction with limiting controls and synchronized closing of the static switch. These tests what Tecogen and Youtility had done during the factory acceptance testing of the stand-alone inverters and the engine-coupled inverters. The performance goal was to observe smooth transitions in the Gen-set controls' responses to different step conditions. Thirteen separate tests were conducted.

The fourth set of tests demonstrated the flexibility of the microgrid while both connected to the grid and islanded, for different loads, power flows, and utility impact. These tests employed "weak grid" inductors in the circuit simulating the microgrid connection at the end of a lengthy feeder. Three sets of tests were conducted.

The fifth and final set of tests began to explore the operational limits of the microgrid with difficult induction motor starting loads. Two primary sets of tests were conducted under "weak grid" conditions.

The testing fully confirmed earlier research that had been conducted through analytical simulations and laboratory simulations and factory-acceptance testing of individual microgrid components. The islanding and resynchronization method met all IEEE 1547 and power quality requirements. The electrical protection system was able to distinguish between normal and faulted operation. The controls were found to be robust under all conditions, including difficult motor starts.

The results from these tests are expected to lead to additional tests of enhancements to the basic techniques at the test bed, tests to improve the business case for microgrid technologies, as well to field demonstrations involving microgrids that employ one or more of the elements of the CERTS Microgrid concept.

CONCLUSION

The objective of the CERTS Microgrid Laboratory Test Bed Demonstration project was to examine the functionality of the CERTS Microgrid concept. Tests performed so far focused on three advanced techniques that are key to the CERTS Microgrid concept: 1) a method for effecting automatic and seamless transitions between grid-connected and islanded modes of operation; 2) an approach to electrical protection within the microgrid that does not depend on high fault currents; and 3) a new method for microgrid control that achieves voltage and frequency stability under islanded conditions without requiring high-speed communication. All three techniques were successfully demonstrated in a carefully orchestrated sequence of five sets of tests by AEP.

The testing fully confirmed earlier research that had been conducted through analytical simulations, laboratory simulations, and factory acceptance testing of individual microgrid components. The islanding and resynchronization method met all IEEE 1547 and power quality requirements. The electrical protection system was able to distinguish between normal and faulted operation. The controls were found to be robust under all conditions.

The next logical phase for research, development, and deployment (RD&D) of the CERTS Microgrid Concept is to prioritize, develop, and demonstrate additional technology enhancements required to optimize the microgrid and demonstrate its commercial viability. Now that the technical feasibility of microgrid functions has been demonstrated in the initial tests, RD&D efforts are needed to accelerate its commercial deployment. This research should pay special attention to economic drivers, such as economic dispatch responsive to pricing signals and demand-management programs and customer willingness to pay premiums for increased power reliability and quality.

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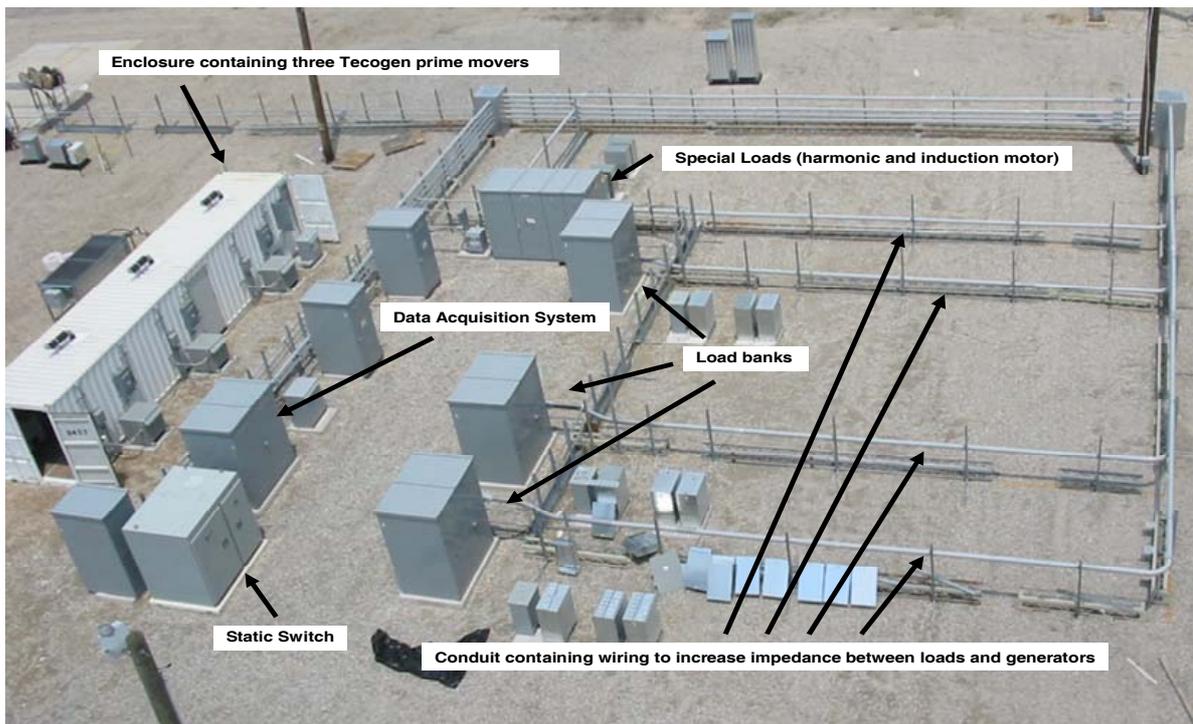


Figure 1. CERTS Microgrid Test Bed at American Electric Power

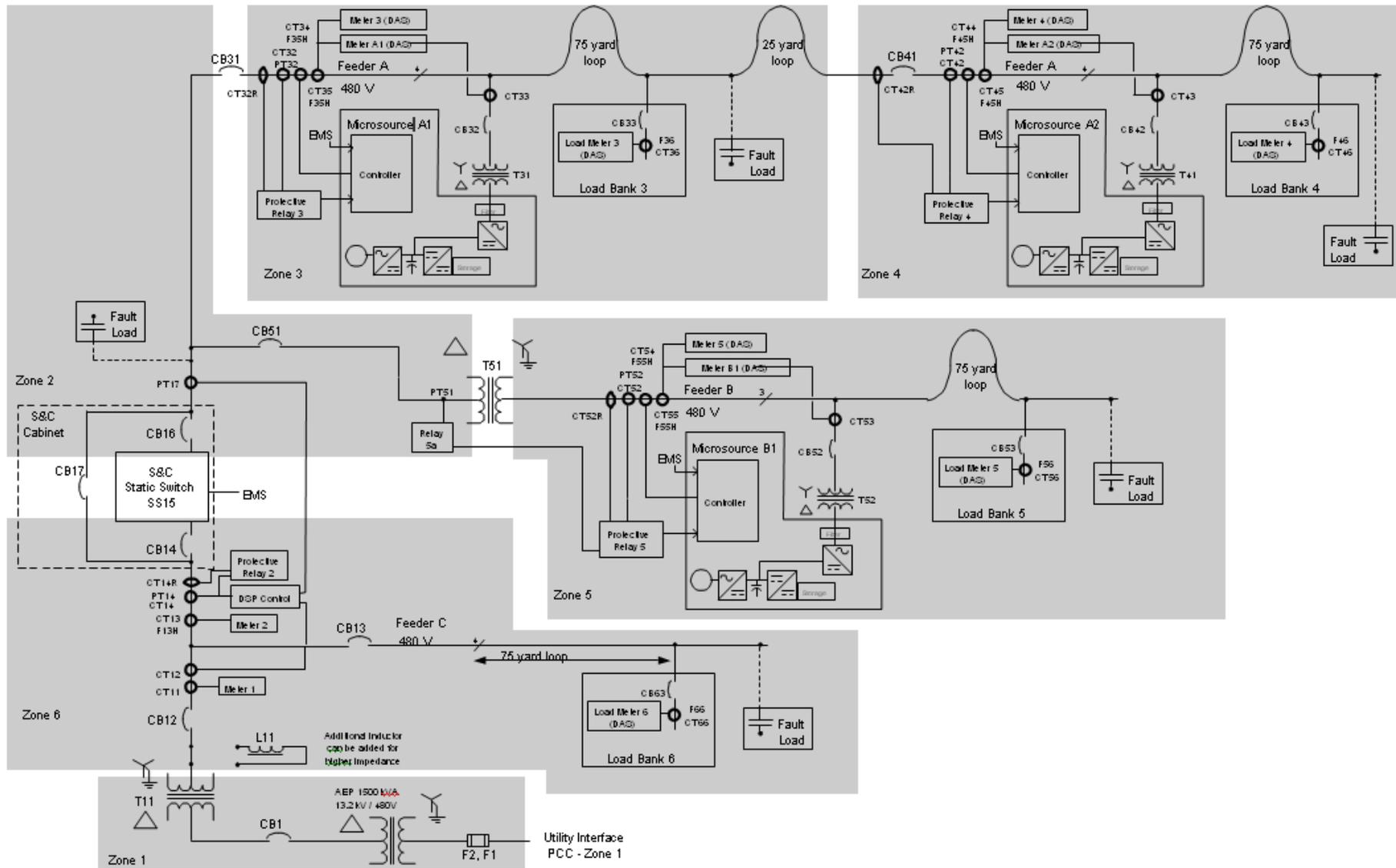


Figure 2. One-Line Diagram of CERTS Microgrid Test Bed



Figure 3. Tecogen Prime Mover with Inverter



Figure 4. The Static Switch