Real-World Performance of a CERTS Microgrid in Manhattan

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***Abstract*—The Consortium for Electric Reliability Technology Solutions (CERTS) microgrid technology enabled the Brevoort, a 1950's era luxury co-op tower in Greenwich Village, NY, USA, to maintain power, water, and heat during the week of wide spread utility outages left in the wake of Hurricane Sandy in late 2012. The microgrid system, anchored by four 100-kW hybrid combined heat and power (CHP), uniquely able to seamlessly transition between grid tie and island-mode operation, powered the entire building including the central boilers, domestic water pumps, elevators, and all apartments, while most buildings in the lower third of Manhattan were without power, heat, and, in many cases, water. The Brevoort co-op board was elected to convert the 20-story building from oil heat to the natural gas CHP system as part of an energy-efficiency green initiative that was fully implemented in 2010. In New York City, these hybrid cogeneration systems can operate in parallel with Con Edison utilities during periods of regularly available power. During a power grid failure, the units, with their permanent magnet generators and inverters with built-in CERTS microgrid technology, will autonomously transition to island mode and continue powering the residences.**

***Index Terms*—Combined heat and power (CHP), Consortium for Electric Reliability Technology Solutions (CERTS), distributed generation, distributed resource, islanding, low emissions, microgrid.**

I. Introduction

THE Consortium for Electric Reliability Technology Solutions (CERTS) microgrid concept captures the emerging potential of using a system approach to distributed generation. CERTS views generation and associated loads as a subsystem or a "microgrid." The sources can operate in parallel to the grid or in island mode, providing high levels of electrical reliability. The system not only disconnects from the utility during large events (i.e., faults, voltage collapses), but also may disconnect intentionally when the quality of power from the grid falls below certain standards [1].

In a real-world application, a high-rise condominium complex in lower Manhattan installed four 100-kW combined heat and power (CHP) hybrid generators [2]. Typically, CHP systems have been employed solely for their economic and environmental benefits. This hybrid cogeneration solution not only offers exceptional full and part load efficiencies as well as near zero emissions, but also allows these CHP units to run as backup generators in the event of a grid disconnect. The four 100-kW units incorporate CERTS microgrid software which allows them to seamlessly transition from grid tie to stand-alone islanded microgrid.

This paper will describe the CHP system and its integration into the building power infrastructure, details of the 100-kW CERTS-enabled hybrid generators, and performance of this system in both a grid tie setting and in island mode as part of a microgrid during the blackouts that followed Hurricane Sandy in 2012.

II. Brevoort Co-Op Objectives

The objective was to design and install an efficient trigeneration system with an integrated microgrid capability so that the site would be able to stand alone during a utility power interruption powered by CHP generators in the system. The trigeneration system would displace utility electricity usage and domestic hot water production year round, preheat the steam used for space heating during the winter months, and power an absorption chiller that would cool the building during the summer. During a power outage, the building and the system would be isolated from the utility grid and continue providing heating, cooling, and power to the residences. In many instances, the complexity and expense involved in enabling a site to convert from parallel grid operation to a microgrid powered by its CHP systems are prohibitively expensive and technically complicated. This project was significantly simplified and the upfront cost was greatly reduced with the application of a microgrid anchored by simple CERTS microgrid design and enabled devices. This design approach tipped the cost–benefit ratio scale for this project, making it not only viable for the Brevoort but a significant value-added proposition over a traditional CHP system with added onsite emergency power generators.

III. CERTS Microgrid Concept

One of the objectives of the CERTS microgrid concept was to reduce microgrid system cost and increase reliability [3], [4]. This includes plug-and-play functionality without communications. Plug-and-play concepts reduce engineering cost and errors since little site modification is required for different applications. Each CERTS device regulates voltage and frequency, both grid connected and while islanded. These key concepts have been demonstrated at the American Electrical Power Microgrid Test Facility, as

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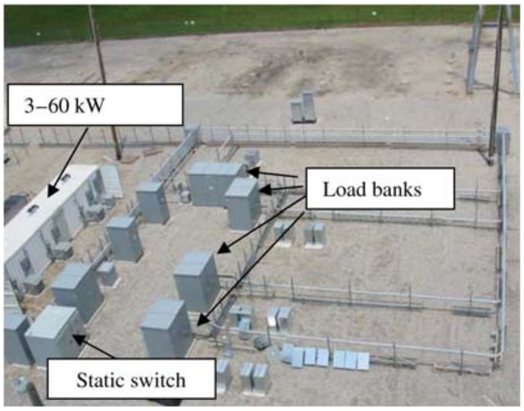

Fig. 1. CERTS microgrid test-bed (AEP's walnut site).

shown in Fig. 1 [5]. This includes transient events such as seamless separation and automatic re-synchronizing with the grid, Class I level power quality during utility faults, large unbalanced loading, and stable operation during major events. The CERTS concept has three critical components: the disconnect switch, the microsources, and loads. The disconnect switch has the ability to island the microgrid autonomously for disturbances such as faults, IEEE 1547 events, or power quality events. Following islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. Re-synchronizing uses the frequency difference across the switch to insure transient-free switching as the voltage phase angle passes through zero.

Each CERTS-controlled source seamlessly balances the power on the islanded microgrid using a power versus frequency droop controller. At maximum output, the frequency controls are designed to drop no more than 1%. If there is inadequate energy to meet the load, the frequency will drop below the normal operating range, signaling the noncritical loads to shed. The coordination between sources and loads is through frequency.

The CERTS sources not only control the voltage, but also ensure that there are no large circulating reactive currents between units. With small errors in voltage set points, the circulating current can exceed the ratings of the units. This situation requires a voltage versus reactive power droop controller so that, as the reactive power Q generated by the unit becomes more capacitive, the local voltage set point is reduced. Conversely, as Q becomes more inductive, the voltage set point is increased. At the Brevoort, this droop is around 5%. In addition to the system voltage stability demonstrated at the AEP test site, an extensive theoretical analysis indicates that the microgrid's stability is independent of the number of CERTS devices. Theoretically, the system will remain stable even as we approach an infinite number of CERTS units.

Tests from the AEP test site demonstrating the dynamics of the CERTS controls are shown in Fig. 2. Fig. 2 shows the response of two sources during an islanding event. In this system, there is no communication between the two units [6]. Before islanding ($time = 0.0$ s), both sources are connected to the AEP system. The real power output of A-1 is 5 kW and reactive power (capacitive) is close to 9 kVAR. Three-phase currents from the Y side of the source are shown in the middle plot and the lower plot is voltage at the point of connection to the feeder. Fig. 2(b) traces are measured at unit A-2. Before islanding, the power output of A-2 is 55 kW and the reactive power (capacitive) is close to 5 kVAR.

The grid-connected microgrid imports 32 kW from the utility. After islanding, the two units independently compensate for loss of grid power. A-2 overshoots its steady-state maximum for less than 200 ms peaking at 70 kW, but then the controls back off the generation, whereas unit A-1 increases its output to meet its share of the loads. The new steady-state operating point for A-1 is 29 kW and A-2 is 60 kW. Note that the reactive output is greatly reduced. Voltage magnitudes are nearly constant for both sources demonstrating the stiffness of the inverter voltages and the microgrid's stability.

IV. DESIGN OF CO-OP'S ELECTRICAL AND THERMAL SYSTEMS

When selecting the CHP component to this system, efficiency, initial cost, life cycle, and ability to maximize load following, and therefore minimize peak usage penalties, were key factors to the design. Based on these criteria, a reciprocating engine-based CHP system was selected over other technology options namely microturbines and fuel cells.

When selecting between reciprocating engine-based CHP options, this hybrid approach was selected for best in class efficiency, part load efficiency, and integrated inverter with CERTS microgrid capabilities. A 400-kW system comprising four 100-kW units (capable of producing 125 kW at peak) was designed for the site (Fig. 3). Although classic CHP applications are designed to base load a facility electrically and to follow thermal loads, utility peak demand charges in Manhattan make it most economical to load follow electrically. Typical average electric usage in the winter for the Brevoort is in the 250-kW range with 350-kW peaking. In the summer, the average is expectedly higher, in the 400-kW range with 550-kW peaking. The site will typically runs three of the CHP units during the winter and runs all four at full capacity to capture demand during the summer thus maximizing efficiency.

When operating in parallel with the grid, the CHP plant maintains a minimum 50-kW import to ensure that local requirements of zero export are met. Fifty kilowatts was selected as this is the consumption of the largest motor in the building: an elevator. If the elevator motor shuts off while the cogen units are producing electricity for it, there is the potential for export in the few moments between the time that the building load decreases and the CHP units respond to the event. At full output, each of the four cogeneration units produces $0.79\ \mathrm{GJ/h}$. This heat is captured from engine jacket using marine headers and from the exhaust with heat exchangers. Water can be heated to 132 °C from the exhaust loop while water from the engine jacket can reach 99 °C. Typical CHP applications combine the heat from the engine jacket and the exhaust. However, at the Brevoort, the space heating in the winter months uses a low-pressure steam loop and not forced hot water which is more common in ideal CHP applications. The higher temperature heat from the exhaust is used to preheat the condenser water in the steam boilers, whereas the lower temperature water from the engine jacket is used to heat the domestic hot water. During the summer, heat that is not used in domestic water

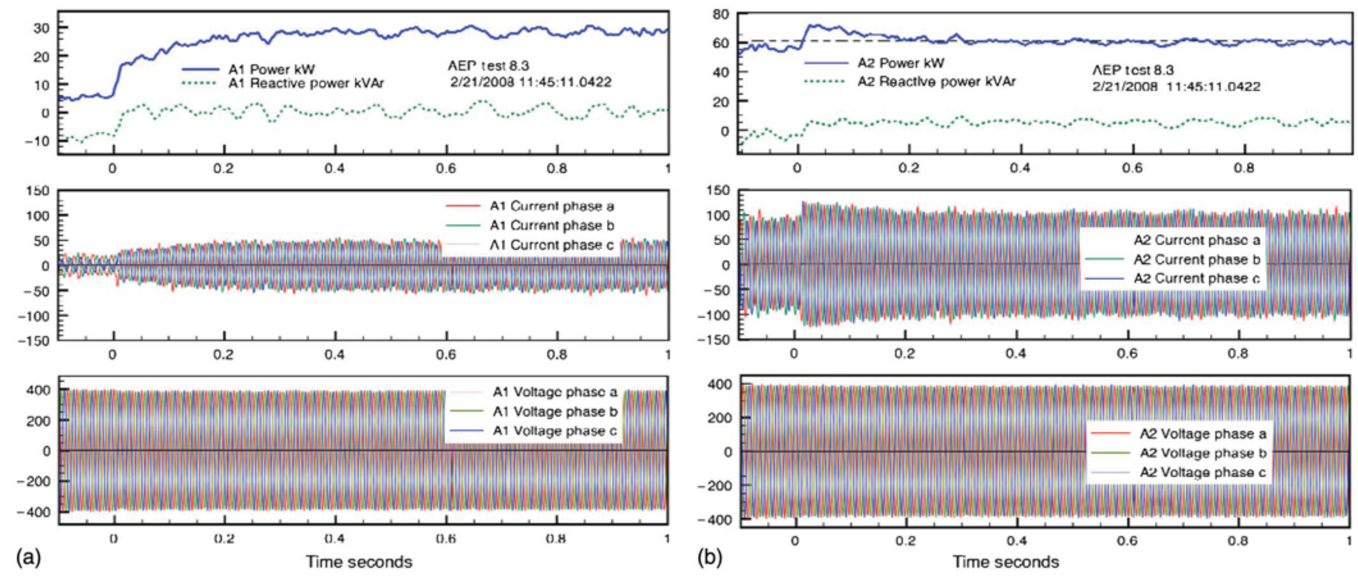

Fig. 2. (a) Dynamic response of unit A-1 and (b) dynamic response of unit A-2.

Fig. 3. Brevoort's trigeneration system.

is used in a 90-ton Yazaki absorption chiller which provides cooling for the residences.

A utility protection panel (UPP) monitors the utility and the cogeneration plant. In the event of a utility outage, the UPP is designed to automatically manage the transition from grid blackout to fully powered microgrid. When the UPP senses that the grid has failed, it will shut down the CHP plant so as to not electrify any portion of the grid outside the building. Next, the UPP will isolate the Brevoort from the grid via a series of circuit breakers and establish a microgrid. Finally, it will power up the units which will continue to operate in an electric load following configuration to power the building. Heat will continue to be available for domestic hot water, heating, or the absorption chiller. In the event that the thermal production exceeds the demand, heat can be rejected via a dump radiator.

The CERTS software allows the hybrid units to self-modulate when in island mode and share the building load equally among the four units without the need for external controls or the master–slave configuration otherwise required for the operation of multiple power generation systems. In addition to simplifying the engineering of the plant and reducing first cost to the Brevoort, the autonomous operation of the CHP modules safeguards the site from a possible master unit failure resulting in the shutdown of all units. If any individual unit fails, the other three will automatically compensate for this loss as they would for any increase in load from the building.

V. Design of Hybrid Generator

The hybrid generator is a natural gas fueled CHP module rated at 100-kW continuous electrical output while simultaneously producing 0.77 per hour of hot water (110 °C). Its overall efficiency is 92%, when all the recoverable heat is used.

The unit utilizes a unique power generation technology made possible from recent advances and cost breakthroughs in power electronics (variable speed drives) and magnetic motor/generator materials (hybrid vehicle drive systems). The product was developed under a major grant from the California Energy Commission's Public Interest Energy Research program and Sempra Utilities (Southern California Gas/San Diego Gas & Electric) [6].

The hybrid module, conceptually depicted in Fig. 4, features a low-emissions natural gas engine, which drives a water-cooled permanent magnetic generator. The engine is operated over a wide speed range, depending on the load requirement, while the power electronics convert the variable frequency output from the permanent magnet generator to high-quality 60-Hz power. Variable speed operation in grid-tie mode maximizes fuel efficiency under part load conditions, while also allowing operation in a "peaking" mode of 125 kW for several hundred hours per year to offset, especially high "on-peak" utility demand tariffs and energy charges or to obtain extra savings from utility demand reduction programs.

This is the first engine-driven product to carry full UL 1741 certification for "utility-safe" interconnection, while also

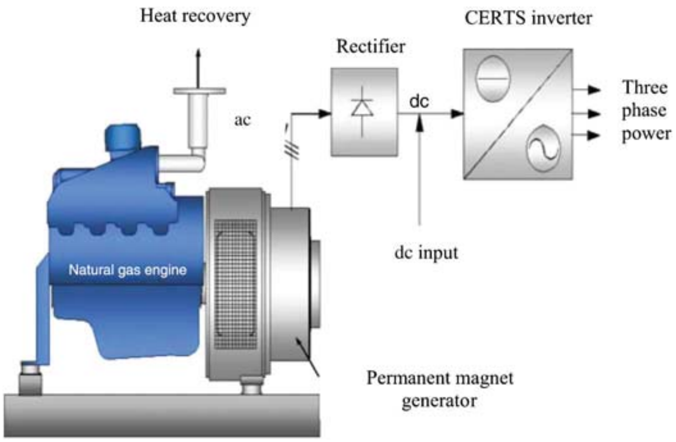

Fig. 4. CHP/CERTS hybrid module.

providing seamless power transfer to stand-alone operation in the event of a power outage. The product features the CERTS control software under a license from the Wisconsin Alumni Research Foundation. These controls have been extensively demonstrated at the AEP Dolan Laboratory (Fig. 1), enabling multiple machines to load-share on an isolated bus, without any interconnecting or supervisory controls [7].

VI. BUILDING DESIGN IMPLEMENTATION

In its original configuration, the Brevoort relied on oil for both its domestic and space heating loads. In the conversion from oil to natural gas cogeneration, the previous equipment needed to be removed and replaced with the cogeneration units and a natural gas powered steam boiler. The cogeneration systems came from the factory in a four pipe configuration with two separate heating loops coming from the CHP units: one from the engine jacket and one from the exhaust. This allows for higher temperatures to be reached in the loop coming from the exhaust. This higher temperature water is used to preheat the condensate from the building space heating loop. The condensate is then flashed in the gas-powered boilers.

The building was submetered, and each condo had its own meter from the electric utility and received its own bill each month. To increase the electric load for the building in order to match the thermal load conversion, the Brevoort overhauled the entire electric infrastructure of the building by changing to a master meter for the site as well as installing building owned submeters for each condo. The Brevoort could have chosen to simply master the meter without the addition of the individual submeters, but as part of their energy efficiency upgrade, they wanted each tenant to be responsible for and cognizant of his or her own energy usages as opposed to instituting a flat communal electric fee.

To stabilize the thermal load throughout the year to better match the electric load now established for the cogeneration plant, an absorption chiller was also engineered into the system. In addition to making use of the excess heat from the cogeneration systems, the absorption chiller also offsets peak electric usage further improving the economics for the Brevoort.

From the first conception to completed installation of the entire system upgrade from oil to natural gas cogeneration with the absorption chiller, the combination of which is commonly referred to as combined cooling, heating, and power, or trigeneration, was about two and a half years. The CHP plant is the primary source for space heating, cooling, and domestic hot water heating.

VII. PERFORMANCE

As Hurricane Sandy swept through Manhattan, the expectation of significant damage to the electric grid spurred the local utility to pre-emptively cut power to the lower third of the peninsula. The Brevoort, located on lower 5th Avenue, found itself without power that evening. The UPP interfacing the CHP plant with the grid was designed to sense grid failure, shut down the plant, isolate the building from the grid, and start the cogeneration units again within minutes automatically. As the minutes passed and the lights failed to come back on, it was determined that one of the automatic breakers governed by the UPP had failed to operate.

With support engineers on the phone, the building superintendent was able to isolate this problem, manually disconnecting the building from the grid and start the CHP plant. The Brevoort stayed in island mode for 6 days as the utility worked to bring power back to the region. During this time, the population of the complex more than doubled as friends and families of tenants took refuge. All of the residences had light, heat, water, and elevator service. As utility power was returned to the area, the Brevoort re-integrated with the grid with the CHP plant running in parallel grid maintaining a minimum 50-kW import.

VIII. CONCLUSION

The Brevoort co-op microgrid project highlights the importance of low-cost CHP units, with plug-and-play features and the lack of complex control systems. Implementation was significantly simplified and the upfront cost was greatly reduced using these concepts. This design approach tipped the cost–benefit ratio scale for this project, making it not only viable for the Brevoort project but a significant value-added proposition over a traditional CHP system with added onsite emergency power generators. Each CHP module is “plug-and-play” and can be applied in a building block fashion to many types and sizes of facilities, and provided power outage security, in addition to their CHP benefits. The expected simple payback of this project is less than 5 years. The actual energy savings for 2013 is \$228 871 based on 2007 costs. It should also be noted that the performance of the Brevoort microgrid during Sandy was dependent on the natural gas supply surviving. In other cases, such as fire and earthquakes, this may not be the case.

The hybrid CHP units’ overall efficiency is 92%, when all the recoverable heat is used and its “ultra” system offers $\mathrm{NO_x/CO}$ emissions comparable to fuel cells [8]. The microgrid software in each hybrid unit allows for autonomous operation when in island mode. This includes sharing the building load equally among the four units without the need for external controls or the master–slave configuration otherwise required for the operation of multiple power generation systems. In addition to simplifying the engineering of the plant and reducing first cost to the

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