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Characterization of Microgrids in the United States

Final Whitepaper

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Introduction

Few microgrids have been installed in the United States. The key defining characteristic of a microgrid is the operation of distributed generators serving separate loads via a non-utility electrical distribution system in a coordinated arrangement offering higher reliability to a multiple facility (or multiple load center) site. Despite considerable research on this topic, the number and location of real world installations and commercial investments has not been published. As more microgrids are installed and operated, lessons might be learned from existing projects that could enumerate their benefits and reduce future costs.

This paper provides initial answers to the following questions:

1. What are the different types of microgrids?
2. How prevalent are microgrids in the U.S.? Who has installed them?
3. What DG technologies are being used? (engines, fuel cells, microturbines, wind, PV)
4. How are these microgrids controlled? Who makes the control equipment? What modifications to the standard generators or control systems were required for protection?

To answer these questions, first the concept of a microgrid is defined. Second, details from specific microgrid installations covering the equipment used and the type of control systems deployed are provided. Finally, an estimate of the market potential for microgrids based on multi-generator sites is presented.

What is a Microgrid?

Microgrids can be grouped into a number of different categories or classes. A basic or "simple" microgrid has certain key characteristics:

- Multiple generators serve load in multiple buildings (frequently in a campus or office park setting) with the generators grouped together in a power plant arrangement.
- The generators and facilities are connected by a non-utility-owned distribution grid (local electric power system, or Local EPS). The Local EPS is interconnected with the utility-owned distribution grid (area electric power system, or Area EPS).
- The Local EPS incorporates microgrid "event detection and response" control allowing the microgrid to detect an event or outage on the Area EPS and to then disconnect from the grid and operate as an intentional island. This microgrid control is able to start-up each of the generators as needed to support islanded operation.
- A master control system located at the power plant operates the generators as needed to both meet loads and provide voltage and frequency support to the Local EPS.
- The generators can serve loads in each of the site buildings on a selective basis. This is accomplished through the use of the Local EPS along with appropriate control and protection equipment.

In this paper, this microgrid is designated a "simple" (Class I) microgrid.

A "master control" (Class II) microgrid has the following characteristics in addition to those of the simple microgrid:

- The generators are distributed among the individual buildings or load centers being served, and accordingly are not tied to the same bus.
- A master control system operates the generators as needed to both meet loads and provide voltage and frequency support to the Local EPS.

A "peer-to-peer" (Class III) control microgrid has following additional characteristic:

- The microgrid control system operates on a "peer-to-peer" basis (no master control), with local control at each generator's location maintaining voltage and frequency stability, and providing power sharing, power flow and waveform control for the building electrical distribution feeders being served by that particular generator or group of generators.

Each microgrid system addresses the unique needs of the site, often including high-speed transfer to meet "sensitive loads". The critical nature of the site loads will determine how quickly the microgrid will need to drop off the Area EPS and switch to distributed generation supply. In the case of critical loads, such as microprocessor-based loads, this transition will typically occur within a quarter-cycle (4 ms) to avoid dropping these loads. This requirement can be met by 1) use of a static transfer switch along with a battery storage system to carry the load while the generators are ramping up, or 2) DG operation parallel to the Area EPS prior to detection and transfer and a static transfer switch. A microgrid may be designed to drop non-critical loads during the transition.

The characteristics of each class of microgrid are summarized in Table 1.

Table 1. Microgrid Characteristics

Microgrid Characteristic	Simple (Class I)	Master Control (Class II)	Peer-to-Peer Control (Class III)
Multiple generators serving loads in multiple buildings	✓	✓	✓
Served by Local EPS	✓	✓	✓
Interconnected with Area EPS	✓	✓	✓
Event detection and response control	✓	✓	✓
Generators located in central power plant	✓		
Generators distributed among buildings (separate buses)		✓	✓
Master microgrid control	✓	✓	
Peer-to-peer microgrid control			✓

Microgrid Operating Modes

All microgrids can operate in one of a number of different modes—

1. Distributed generators provide baseload power to a portion of the site loads, with the Area EPS providing supplemental and backup power (***Mode 1 - Partial Baseload***);
2. Distributed generators provide power to all site loads, with the Area EPS providing backup power (***Mode 2 - Full Baseload***);
3. The Area EPS provides power to all site loads, with distributed generators providing backup power; in some cases, the DG units can provide peaking service as well (***Mode 3 - Backup/Peaking***).

Examples of these modes are given below.

<u>Partial Baseload - Mode 1</u>. Distributed generators provide baseload power to a portion of the site loads, paralleling with the Area EPS that provides supplemental and backup power. A leading example is campuses or groups of buildings with multiple generators operating in a baseload mode, but using the Area EPS to meet peaking needs. This would include combined heat and power (CHP) applications providing both electricity and thermal energy. The DG equipment would be designed for continuous operation and paralleling with the grid. The DG units feed a non-utility-owned distribution system within the campus. When a fault is detected on the Area EPS, the microgrid disconnects from the Area EPS and operates as an intentional island. The transition to microgrid supply is typically accomplished through the use of paralleling switchgear. In most cases where the site generation is not designed to carry full site load, less essential loads will need to be dropped.

<u>Full Baseload - Mode 2</u>. Distributed generators provide power to all site loads, paralleling with the Area EPS for backup power when needed. This would be similar to the example given for Mode 1, but with the microgrid being designed to meet all site loads. The Area EPS is used for backup power only, but the same transition switching requirement applies. When a fault is detected on the Area EPS, the microgrid disconnects from the Area EPS and operates as an intentional island. With the distributed generation designed to meet full site load, no load will need to be dropped.

<u>Backup/Peaking - Mode 3</u>. The Area EPS provides power to all site loads, with distributed generators providing backup power. An example would include campuses/multiple buildings using the Area EPS supply to meet all site loads. The microgrid serving the campus (or group of buildings) would be based on light duty backup generators designed to pick up the site loads when an event or outage occurs on the grid. The backup generators are typically located in some or all of the individual buildings being served, but they can be dispatched directly in response to an event on the Area EPS.

The nature of the site load (i.e., critical/non-critical) will determine the required speed and "seamlessness" of the transfer needed in Mode 3 applications. Sites with critical loads will use static transfer switches and battery storage to make the transfer seamless (often referred to as a "make before break" transfer). Sites that can tolerate a short outage will manually or semi-automatically disconnect from the grid, and then start their emergency light-duty generators (often referred to as a "break before make" transfer).

In some cases, microgrids operating in Mode 3 have the ability to be used for peak shaving, but additional equipment (e.g., ATS breaker wrap-arounds, described subsequently in this paper) are required.

Focus of this Paper

This paper sought to highlight the coordination and control strategies that make a microgrid unique. One area of high interest is the current application and future potential of advanced control strategies, technology and hardware to support the operation of peer-to-peer (Class III) microgrids. This class represents the most exciting and flexible form of future microgrids, offering the greatest potential for improving overall power system reliability. The microgrid sites identified in this paper mostly represent master control (Class II) microgrids, primarily due to the limited development of peer-to-peer (Class III) applications to date. At least one Class III site is discussed in detail.

While not a primary focus of this paper, the most common form of microgrid found today is the simple (Class I) application, a site with multiple generators all tied to the same bus to serve building load. The site is tied to the Area EPS and operates in one of the three operating modes described above. A local distribution system serves the facility, and multiple buildings or load centers are present. The simple microgrid may offer higher reliability to a multiple facility (or multiple load center) site.

Even more common than the simple microgrid is the DG installation serving loads in a single building. Not a microgrid, this application nevertheless in often interconnected with the Area EPS, and can operate as an intentional island in response to an event on the grid. Another example of a DG installation that does not qualify as a microgrid is an isolated Alaskan village where no Area EPS is available for interconnection.

Microgrid Configurations

Figure 1 illustrates a simple (Class I) microgrid.

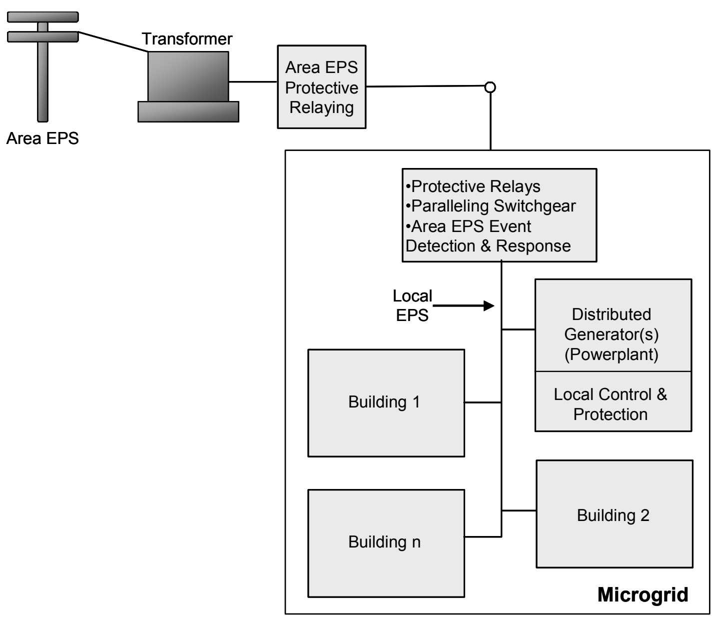

Figure 1. Simple (Class I) Microgrid

Figure 2 illustrates how a master control (Class II) microgrid might be configured and interconnected. A peer-to-peer control (Class III) microgrid is shown in Figure 3.

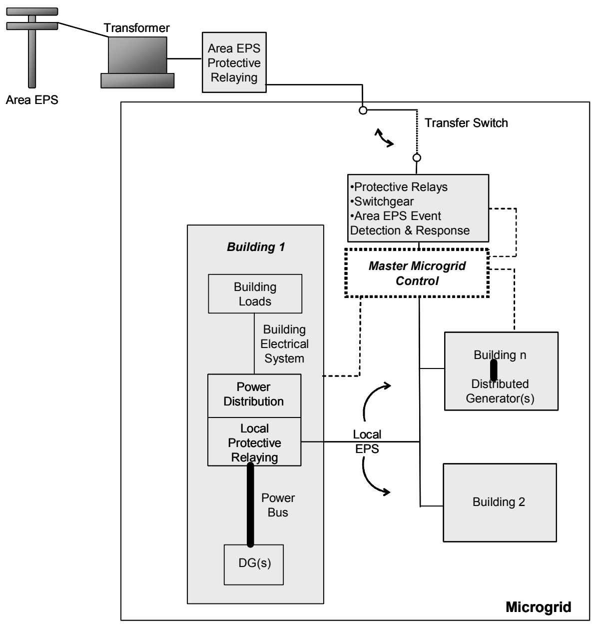

Figure 2. Master Control (Class II) Microgrid

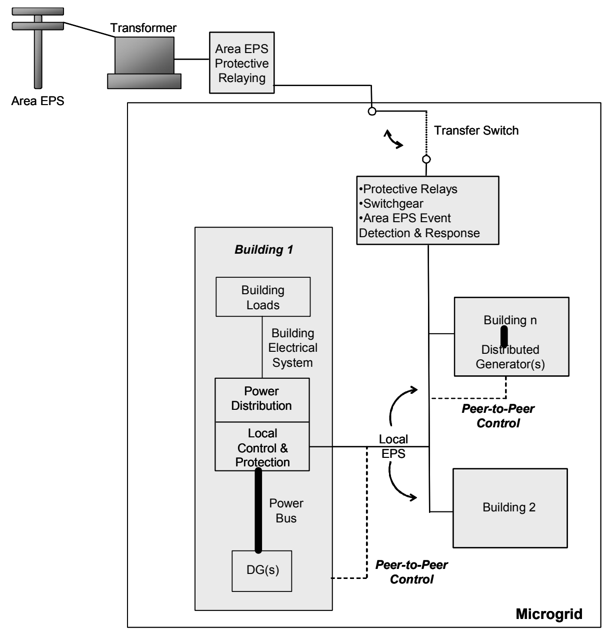

Figure 3. Peer-to-Peer (Class III) Microgrid

Microgrids Currently Installed/Planned in the U.S.

A handful of existing sites meeting the definition of a microgrid have been identified. They are presented in chronological order from early installations to more recent and more advanced experiments. Following this summary of microgrids, this paper includes a brief discussion of other interesting projects which some developers, control system manufacturers, and end-users call microgrids, but do not really meet the definition herein.

University Campus Power Grids

Since 1999, Wellesley College has owned and operated its own electric utility plant with a capacity of 7 MW, which is adequate to meet the entire campus demand. They operate at 4,160 volts using one substation from which power is distributed across the campus. The Wellesley local grid is connected in parallel with the Area EPS. Wellesley uses the Area EPS as a backup when their DG fails. In the event of a utility power failure, Wellesley's control system disconnects the microgrid from the Area EPS. The control system cannot start up or operate individual engines to just meet demand. This is a simple (Class II) *full baseload* microgrid (Mode 2). This type of system (either simple or master control microgrid) may be a common configuration for university campus systems such as those noted in Table 2.

Table 2. Example University Campus Systems with CHP

University	MW	% of Campus Electricity	Number of Heating Plants	Number of Cooling Units
Iowa State University	34	75	1	Single
Loma Linda University	10	95	1	Single
Michigan State University	61	86	1	Multiple
SUNY, Stony Brook	45	100	1	Multiple
University of Alaska, Fairbanks	22	100	1	Single
University of Colorado, Boulder	16	100	1	None
University of Illinois East Campus	20	100	1	Single
University of Texas, Austin	85	100	1	Multiple
Wellesley College	7	100	1	Single
Yale University	22	95	2	Multiple

Pleasanton Power Park

During 1998 the Pleasanton (near Livermore, CA) Power Park designed a microgrid for reliably powering a commercial office park campus. The implementation date was 2001. Intergy Solstice Group was the lead energy systems design and installation firm, in conjunction with Department of Energy and California Energy Commission grants. The approach was to interconnect photovoltaic rooftop arrays on three of the buildings totaling 340 kW, one mid-size fuel cell within a building, and smaller microturbines within each campus building – all connected to the utility grid as a backup. The system also included a 100 kWh backup storage device for increased reliability. High reliability was marketed as the key benefit to prospective tenants requiring "premium power". Overall savings were projected from use of DG, more efficient retrofitted building equipment, and careful energy management. The energy management system was designed for remote web-based observation and control.

During development, Intergy noted several obstacles to development arising from the fact that there was no regulatory precedent that allowed development to progress quickly. They had to address utility standby charges, master metering, local building permits and codes, property line requirements, FERC jurisdictional requirements, and ways to obtain credit for enhanced utility grid benefits. They examined options such as the use of pilot programs, legislative and regulatory changes, and unusual property line configurations. Ultimately a plan for development within the existing regulatory structure was identified, but as a unique solution Intergy felt the final solution was not readily duplicable elsewhere. Indeed, such siting challenges remain for most DG and microgrid installations today.

Technically, this microgrid was developed using traditional control system technologies. Documentation suggests the generators were all interconnected to the utility bus. Unfortunately it was not possible to locate anyone connected with the project as Intergy went out of business, and their lead people moved on to other firms that subsequently also have gone out of business. Therefore no lessons have been garnered about microgrid control systems from this early experiment. Full operation has not yet been achieved.

As a postscript, before going out of business, Intergy Solstice Group also installed a multiple generator grid within the Four Times Square (New York City) real estate development during 2000-01. This project concentrated on using PV and fuel cells, and promoted not only reliability but also low emissions and emission trading credits. Its financing was partly based on government subsidies. Both of these examples appear to be partial baseload (Mode 1) microgrids, with Pleasanton Park a peer-to-peer control and Times Square a master control microgrid.

Larger Multiple DG Units Operated in an Array

More recently Equity Office has followed a similar business model, installing DG in office buildings where the combination of energy cost savings and reliability have proven to have benefits exceeding costs. As just two of many examples, during 2003-04 Northern Power Systems helped Equity Office install multiple gensets in 2 downtown San Francisco office complexes. However, in most Equity Office projects while the gensets have been installed to feed power to the building's distribution grid, they are individually interconnected to the utility bus, and when the utility grid goes down each one disconnects from the grid using their local control system. The generators do not interact with a master supervisory control system or directly control each other. These are either "simple" or "peer-to-peer" microgrids operating in a partial baseload mode.

Many existing multiple generator installations serving multiple buildings may have similar control configurations, with a mixture of automatic transfer switches and manual switches. A few examples of multiple generator grids that may be configured in a similar manner are noted in Table 3. Each of these plants uses natural gas as their primary fuel.

Table 3. Example Multiple-DG Grids

Plant Name	Interconnect With Utility	Industry	Number Gensets	Total MW	State	Technology	Application	Start Year
San Juan Basin Gas Plant	Public Service Company of NM	Oil Extraction	4	8	NM	Turbine	Baseload	1986
Central Production Facility 2	Arctic Utilities Inc	Oil Extraction	4	14	AK	Turbine	Baseload	1983
Blackjack Creek Treating	Gulf Power Co	Oil Extraction	4	2	FL	Turbine	Baseload	1975
Grayling Platform	Homer Electric Association Inc	Petroleum Refining	4	3	AK	Turbine	Baseload	1967
Whiting Refinery	Northern Indiana Public Service Co	Petroleum Refining	4	64	IN	Steam Turbine	CHP	1955
Formosa Plastics	Entergy Gulf States Inc	Chemicals	5	144	LA	Steam Turbine	CHP	1990
Goodyear Beaumont Chemical Plant	Entergy Gulf States Inc	Chemicals	5	35	TX	Combined Cycle	CHP	1987
ExxonMobil Baytown Olefins	Center Point Energy Houston Electric, LLC	Petroleum Refining	8	185	TX	Turbine	CHP	1989

Similarly, many critical power needs customers have installed multiple emergency backup generators to meet their campus needs. This includes hospitals, universities, jails and airports. For example, Benefits Healthcare in Great Falls, Montana just installed their third 1,500 kW engine genset. In this instance, each of the 3 generators is interconnected to the electric utility bus and to the entire hospital campus distribution system. Since their economics cannot compete with utility supplied power, they are only used as backup devices. During a utility power failure, load will be automatically transferred to one of the gensets. Backup generators 2 and 3 may be manually switched onto the local distribution system if needed. The DG system feeds a non-utility-owned distribution system that serves multiple buildings. This system provides redundancy as well as easy genset testing and maintenance. This is a simple, backup power microgrid.

Microgrids on Army Bases

Encorp has made a corporate commitment to build and install commercial microgrids. Encorp has found that by exploiting real time price signals and then by using real time dispatch, users can make money deploying microgrids. In building microgrids, Encorp supplies all the control systems except for those already on the gensets and some of the supervisory systems – including switchgear, meters, general controllers, and monitors.

Encorp has, or is planning to, supply the control systems and equipment for installing microgrids on three Army bases. Their first installation of this type was at Fort Bragg (Fayetteville, NC). This initial project used Honeywell supervisory systems together with Encorp control equipment.

The Fort Bragg project was designed to save money, produce energy security and enhance power reliability, and to provide full parallel interconnection with bi-directional power flows inside the microgrid. Existing backup/emergency generators were retrofit for centralized control and remote operations and management. After completing 3 phases of development, there are now 15 gensets with a total capacity of 8 MW interconnected with each other and with 3 Carolina Power and Light substations. The gensets are interconnected with transfer switches and with ATS breaker-around solutions so that they can automatically be dispatched to export power to the utility during peak price periods, but still be operated as an army base island during utility power failures (see Figure 4).

These generators are not expected to be used for baseload or CHP applications, but are operated only a few hundred hours per year. They are networked and automated to optimize the dispatch sequence (and the control system allows users to select a genset start/stop sequence order), so this approach ensures that the desired gensets are online to peak shave closely following the demand load. However, the controls do not allow for quick transfer of load from one genset to another. This is a master control microgrid operating for backup/peaking.

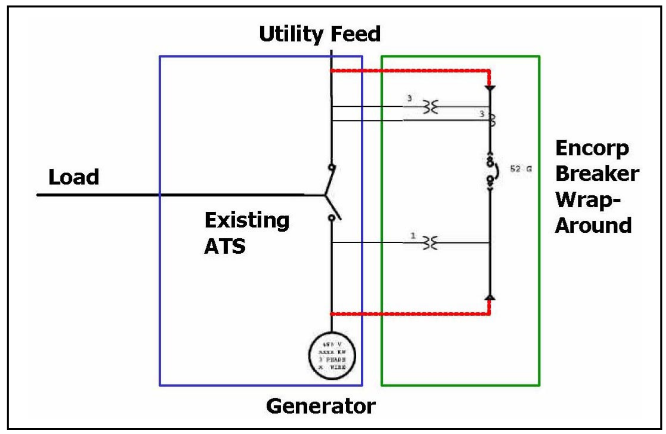

Figure 4. Breaker-Around Solution at Fort Bragg

Encorp is now supplying the control systems and equipment for building a quite similar microgrid installation at Fort McPherson (Atlanta, GA). The Savanna Army Depot (Savanna, IL) will be Encorp's third project. While it is not commissioned yet, the units are in production and may ship during the middle of 2005.

A key lesson learned from these projects is that standard manufacturer equipment can be used to build complex microgrids with limited, if any, modifications. In particular, Encorp's digital platform does not require third party monitoring components for engine, generator and transfer switches.

Mad River Park Microgrid

Northern Power Systems has been developing the Mad River Park (Waitsfield, VT) microgrid during 2004. The project plans to go well beyond the type of microgrids often deployed in universities and on military bases. This is an aggregate 350 kW generation plus storage network that is interconnected in parallel with the local electric utility grid. The microgrid is housed in Northern Power's new headquarters facility, and aside from its

Figure 5. Mad River Park

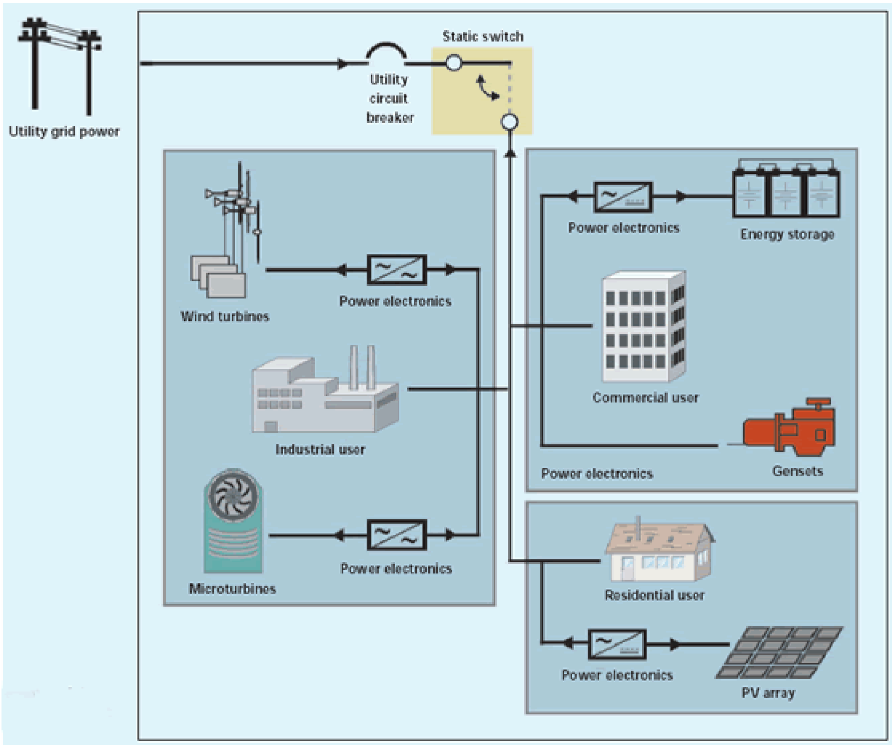

Figure 6. Schematic of Northern Power System's Microgrid

experimental/research quality to verify equipment specifications and ratings under real load conditions, it is expected to provide increased power quality and reliability to users.

The project is being supported by the Washington Electric Cooperative (WEC), the Vermont Department of Public Service, and the U.S. Department of Energy. The project serves as a fully operational demonstration of the capability and benefits of clustering tightly integrated, small-scale generation, storage, and distribution technologies including engines, microturbines, wind turbines and photovoltaic panels. The system features multiple generation and storage devices, and will connect to five commercial and industrial facilities, plus 12 homes within the park.

The control system is capable of being programmed to operate in several distinct modes, ranging from total isolation from WEC's system during the occurrence of specified power events (such as voltage sags, spikes or transients), to grid-following mode. Power coming from the local WEC substation is monitored via a microprocessor-enabled protective relay, which detects the occurrence of scheduled or unscheduled power events and enables the system to quickly island the park. However, operating results are not yet available.

In the May-June 2004 edition of *Cogeneration and On-site Power Production*, Jonathan Lynch, Chief Technology Officer with the Power Technology Group of Northern Power Systems, Inc. made the following remarks about their system:

> "A microgrid power network is defined as two or more DG assets configured in a network and capable of operating either in parallel with, or independent from, a larger electricity grid, while providing continuous power to multiple load centers or end-users. The DG assets may be combinations of power generation and energy storage devices. A Microgrid power network can island from a larger electricity grid and continue to meet the power needs of the loads within the network without interruption.

> Microgrid power systems are a way to apply the economic and premium power advantages of DG on a larger scale than individual end-use customers, for applications like campuses, industrial parks, or military bases. Systems can be configured to provide the level of energy service required by connected users. An energy end-user connected to a Microgrid power system can benefit from a secure, high-reliability, and high-availability power source that can be configured to withstand both short- and long-term interruptions in the utility supply system, while supplying continuous high-quality power to critical loads. Microgrid power systems can have high "fault tolerance", and can be configured to be essentially immune to intentional or accidental damage in the centralized utility power network.
>
> Microgrid power systems can be designed to present themselves to the utility system as a single dispatchable load. The multiple generator, storage and load devices encapsulated in the system can be aggregated into a single entity, as far as the utility is concerned, with the capability of being dispatched like a controllable load during periods of peak demand.
>
> Microgrid power systems can be designed and deployed using conventional internal combustion engine and combustion engine-based DG assets. However, the emerging generation of advanced, power converter-equipped DG and energy storage devices has the potential to provide additional functionality that will make it easier to configure and deploy power systems in the field. In addition to the high efficiency, low-emissions output, and low-maintenance advantages possible with advanced DG devices, additional power network capabilities can be incorporated through recent advances in power converter control technology. These advances can enable new, high-performance features such as "plug and play" capability, inherent harmonics mitigation, and high-speed distribution support. Using this power converter-based Microgrid power system architecture could allow wide-scale deployment of DG equipment and renewable energy resources in the utility power system."

The Mad River Park control scheme appears to be different than the others described in this paper. An inverter-based genset controller is installed at each DG unit, and it appears a peer-to-peer communication network links each controller. This is a peer-to-peer control, partial baseload microgrid.

Detroit Power Pavilion Microgrid

DTE Energy Technologies, a non-regulated subsidiary of DTE Energy, has an ongoing $5.4 million contract with NextEnergy to develop, construct, operate and maintain a state-of-the-art microgrid at the 5,600-square-foot Power Pavilion in Detroit. This microgrid project includes the use of fuel cells, Stirling engines, combustion engines, microturbines and PV. The microgrid includes underground electrical and thermal distribution systems to provide electricity, heating and air conditioning to NextEnergy's own facility. In addition, the microgrid has the capability to serve the broader energy needs of prospective buildings to be located within "Tech Town," a research and business technology park under development on the nearby campus of Wayne State University. One goal is to establish Michigan as a leader in these technologies.

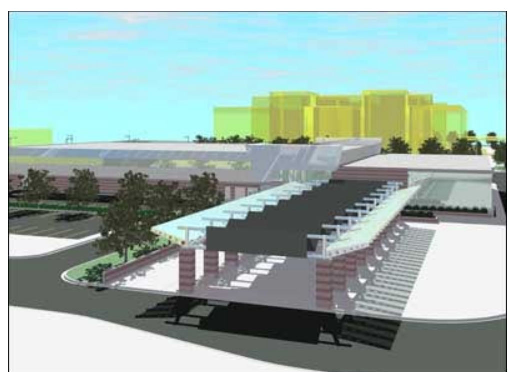

Figure 7. Detroit Power Pavilion

The project is expected to be online between February and May of 2005. The main purpose of the project is to learn about what works and what does not. It is not a typical DG project with a goal of learning about DG technologies nor was it built to produce power for a particular application. The point is to learn about control systems and how to combine multiple technologies. However, since it is not yet online, the verdict is out on what does work until more experiments are performed. DTE is using standard control systems and equipment in putting this microgrid together. The microgrid does parallel with the grid and can be islanded. Enough of this system is now in place that it can be visited to collect detailed insights. However, some of the experimental results may remain proprietary to DTE. This is currently being designed as a master control microgrid operating in full baseload mode.

Mobile Air National Guard Microgrid
NextEnergy started a new project for the Air National Guard in November 2004. They hope to be online with the results in 9 months; however they are currently just entering the study phase. The unusual major issue being addressed is the need for mobility, that is, the need for the microgrid control system to be able to be moved anywhere within 48 hours. Such mobility is in response to a need for homeland security. The project expects to include a combination of as yet unspecified generation technologies, but it will link and control a number of 50-250 kW gensets that are already installed on various air national guard bases. NextEnergy plans to design a microgrid control system for use with backup gensets that already exist, and this control system will be mobile. What is clear to the NextEnergy project manager is that a very sophisticated control system will be needed. This project is emerging as either a master control or peer-to-peer control microgrid.

Other Possible Microgrids
Other possible microgrid sites that were identified during this brief review include:

- Hunt – a residential subdivision in Texas (Mode 1).
- America Online – a campus-wide backup power microgrid for extreme reliability (Mode 3).
- Fort Belvoir – often mentioned as a microgrid (Mode 3).
- TwentyNine Palms – CHP installation that is sometimes called a microgrid (Mode 2).
- Fort Huachuca, AZ – possible Mode 2 microgrid utilizing military approach to establishing "energy surety zones."

No details were secured for these installations. They may be variants of noted examples.

Other Installations Not Considered Microgrids

These installations can be islanded or operated in parallel with the grid, but the distributed generators and the load are all connected to the same bus. They are installed with standard control systems components. While not considered microgrids, they do reflect some of the microgrid characteristics.

Fuel Cell Arrays
During 2001 an array of 6 fuel cells manufactured by United Technologies Corporation (UTC) was installed at a Middletown, CT juvenile training center site. Each was a 200 kW unit for a total capacity of 1.2 MW. Similarly, a 7-unit UTC fuel cell microgrid (1.4 MW) is being installed for Verizon on Long Island. After some delay, the installation is expected to be completed by the spring of 2005.
Indeed it is common for both fuel cells and microturbines to be deployed in such multiple unit arrays. This configuration provides redundancy for higher reliability, allows any one unit to be taken down for maintenance, and allows generation to more closely match demand as units are cycled on and off to follow load demand.

DG systems that are often installed in arrays sometimes have genset control systems designed to be easily integrated with a supervisory control system made by the DG manufacturer. Capstone's latest PowerServer can control up to 100 microturbines, allowing for load following, peak shaving, dual mode, automatic switching, and runtime balancing.

Harbec Plastics
Harbec Plastics Inc. (Ontario, NY) makes complex plastic parts, ranging from low-volume prototypes to large-quantity production items, for automobile, computer, and medical device manufacturers that have intense time-to-market pressures. Harbec's computer-controlled systems are so sensitive that even momentary outages or voltage sags can cause significant problems. During 1999, Harbec endured three separate power fluctuations that led to prolonged shutdowns, lost production, and missed deadlines. Several hours were required to reprogram and restart after each unplanned shutdown.

Clearly, reliable electricity is very important to their operations. Accordingly, Harbec assembled an extensive array of 25 gas-fired Capstone 330 Microturbines and a 250 kW wind turbine during 2001-03. This system generates 100 percent of Harbec's energy needs. While they designed and built their system for power quality reasons, they found that it also can save on power costs even while stabilizing their energy bill and giving them control over environmental emissions.

The facility's parallel connection to the grid is maintained only for backup. Today it costs $1,100 per month to maintain a backup connection to the grid, and Harbec expects this price to double or triple when a new standby tariff takes effect. This possibility is so daunting that Harbec is now considering investing in a 600 kW bio-diesel generator for additional backup capability and then disconnecting entirely from the electric utility grid.

This array of generators relies on the utility grid as a backup, and islands when the grid goes down. If Harbec decides to disconnect from the grid entirely then their control systems will not need to sense nor respond to utility power failures. However their control system will still have to manage internal generator power failures and rapidly switch on different generators to respond to load.

DG Technologies Currently Being Used in Microgrids

As illustrated in the case studies, any generation technology can be used within a microgrid. Further, there are no size limits as microturbines, small fuel cells, small wind turbines, and large reciprocating engines have all been deployed within microgrids. Electricity storage is typically used if critical system loads are being served. Partial and full baseload microgrids typically require continuous-duty DG equipment such as microturbines, fuel cells, combustion turbines, or non-emergency reciprocating engines.

Microgrid Control Systems

Encorp is one leader in designing and building microgrid control system solutions. Northern Power Systems and NextEnergy have been using other manufacturer's equipment to build their microgrid solutions. Other developers use combinations of off-the-shelf equipment when building their microgrids. For systems that require it, proprietary supervisory master control systems are used to control and sequence individual DG units.

Some currently available paralleling switchgear can also control multiple DG units and act as a supervisory control system for microgrids. As an example, Kohler's PD Series can parallel multiple DG units to the utility, island during an Area EPS outage, and optimize the number of generators based on local demand (see Appendix B for product specification sheet).

Developers are working with existing generator control packages. Most of these genset controls, such as Capstone's, are designed to be deployed in microgrids. Systems using arrays of identical gensets require supervisory controls; this is the only commercially available technology today. Peer-to-peer control, when available commercially, will offer increased flexibility, robustness of operation, and improved power reliability and security.

Capstone microturbines have a built-in integral MultiPac controller feature that enables from 2 to 20 units to be operated as a single system. Special cables are required to connect the microturbines. Communications, control, and power output are from a single point. This feature is functional in both a grid- connected and stand-alone mode of operation. If one unit in the system fails, the others will increase their output to compensate.

The Mad River Park project, using proprietary inverter-based genset controls, appears to be the only proposed microgrid that is truly peer-to-peer and plug-and-play with the control logic built into each genset controller. Any genset, as long as the Mad River Park inverter-based control system is used in additional to the genset controller, can be added to their microgrid.

Potential Market for Microgrids

Microgrids may be installed either by converting existing DG into an interconnected operating grid, or they may be developed as "Greenfield" projects. To gain perspective on both aspects of the potential market for microgrids, a brief analysis is now presented.

First, the number of locations where multiple DG sized units currently exist was reviewed. For this analysis, power generators using any technology up to 60 MW in size were considered. DG units reported to the Energy Information Administration (EIA) as being in operable condition as of 2003 were considered. This data source does not include the 80% of all generators that are only operated for emergency/backup purposes few, if any, hours per year. The units shown in the EIA database would be classified as Mode 1 or 2 microgrids – those that are baseload/CHP applications and parallel with the grid. The analysis counted the number of sites with at least 3 onsite generators that potentially might be operated as a microgrid (some of them may be already acting as microgrids). The results are shown in Table 3.

Table 3. Number of Potential Microgrid Sites by Industry and Number of Generators

Number of Generators at Site	3	4	5	6	7+	Total Sites
Paper	31	22	11	12	16	92
Petroleum Refining	18	8		1	6	33
Food	17	6	3	2	5	33
Chemicals	11	4	7	1	3	26
All Other Industries	8	9		3	6	26
Universities	11	6	2		4	23
Oil and Gas Extraction	11	9	1		1	22
Hospitals	12	6		1	3	22
Sewer Systems	11	2	2		4	19
Primary and Fabricated Metals	7	5	3	2	2	19
Business Services	6	1	2	2	1	12
Textiles	4		2		2	8
Public Buildings including Military Bases	4	2	1		1	8
Metal Mining	3		2		1	6
Cement		3	1	1	1	6
Lumber	3		1	1		5
Water Supply	3		1			4
Natural Gas Transmission	1	1		1		3
Transportation Equipment	1	2				3
Finance, Insurance, Real Estate			1	2		3
Electronic Equipment		1	1			2
Total Sites	162	87	41	29	56	375

Source: Energy Information Administration Form 860, 2003. Does not include all small generators under 1 MW in size; most of the excluded smaller generators are primarily used for emergency/backup operations.

It is likely that some of these existing installations can currently operate as an island. However, many of the others generate power that supplements utility-provided power for their operations. Thus they have the potential to be converted into microgrids. For instance, there are indications that some municipal wastewater treatment systems are in the process of converting their generators into a microgrid of sorts using automated control systems (see the Hyperion project in Attachment B).

Two-thirds of the identified potential microgrid sites have only 3 or 4 generators. These may require less sophisticated control systems than integrating a larger number of generators. Currently there are at least 126 sites with 5 or more generators onsite that might be integrated into a microgrid.

The largest potential microgrid industries are paper, petroleum refining, food and chemicals, if only the conversion of existing sites is considered. Most of these sites use inexpensive byproduct fuels and produce both power and heat for local operations. Since there is little data on the number of campuses/multiple facility locations served by multiple backup power DG installations, it is difficult to estimate the potential number of Mode 3 microgrids.

To estimate the market potential for new Greenfield microgrids, consider the existing installed base of DG units and the additional market potential for DG. At the end of 2003, there were 151 GW of reciprocating engines, combustion turbines, and fuel cells between 50 kW and 50 MW in size installed in the U.S.[1] Looking forward a good forecast of additional market potential is 80 to 177 GW.[2] Thus the

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[1] *The Installed Base of U.S. Distributed Generation, 2004 Edition*, Resource Dynamics Corporation, 2004.

existing installed base could expand between 53 and 117 percent. In short, a good rule of thumb is that about as many Greenfield microgrids might be economically installed as there are potential conversion sites. These sites may be in different industries than the existing conversion market.

Conclusions

Most players in the DG industry, including equipment manufacturers, developers and end-users consider a "microgrid" to mean the use of multiple DG units at a site with multiple buildings (e.g., a campus) and a non-utility-owned distribution system. This paper has sought to clarify the microgrid market by defining simple, master control and peer-to-peer control microgrids. It is the area of peer-to-peer control that offers the greatest potential for improving overall power system reliability and security. The need for advanced control strategies, technology and hardware to support the operation of peer-to-peer microgrids is real—more work needs to be done in characterizing current technology status and experience to date.

Research in support of this paper indicates that some microgrid configurations automatically switch on one larger generator using an automatic transfer switch, and additional generators must be switched on manually to provide additional capacity. The Encorp army base installations take this one step further by having the supervisory control systems automatically switch on and off just the necessary generators to follow the load. The Mad River Park project may offer a different control scheme – peer-to-peer with the control logic shared between the inverter-based genset controllers.

The few master control and peer-to-peer control microgrids that have been installed have either relied in part on government funding (state and federal grants, experiments, work on military bases) or they were built somewhat by accident, without the owner realizing that the solution to their cost/reliability needs was a microgrid. Microgrid operating experience is limited, and a number of new installations are just now being completed and may go online during 2005. Thus no operating data is yet available. It would be most useful to continue tracking all these projects for lessons to be learned.

Recommendations for Future Work

A follow-up phase to this current effort is recommended to expand the level of detail on each identified microgrid facility. We will also seek to collect data on the sites identified as "possible microgrids." A proposed Phase II will build upon the information developed in this Phase I, adding considerable detail. First, we will expand upon the initial inventory of installed islandable microgrids by phone interviewing (from our list of existing contacts):

- Leading control system manufacturers to determine whether they have sold controls for islanded microgrids,
- DG installers to learn what microgrids they have installed, and
- DG manufacturers to ask whether they are aware of any instances of their equipment being used in microgrid installations.

For this expanded list of islandable microgrids (possibly 10 to 15 total sites), we will interview both the installer and the operator of the identified installations to determine details of their control systems and any necessary modifications to the control system hardware or software. We will also ascertain their experience in operating the system, and highlight the key characteristics (including similarities and differences) of each of the sites. From this we will distill helpful lessons. A key focus of the Phase II effort will be to refine our characterization of existing sites regarding the exact means of generator supervisory or local control; interconnections between the generators, the Local EPS and the site loads;

[2] *Distributed Energy Resources: An Integrated Market Assessment*, Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington DC, January 2004.

and the equipment installed for sensing Area EPS operating status, disconnecting and intentional islanding. 20-40 page white paper will summarize the results.

Appendix A. Questions Asked of Developers, Owners, or Operators

1. Why was the microgrid installed (quality, reliability, power cost)?
2. What is the nature of the installer (company, industry, campus)?
3. During normal operation, does the microgrid parallel with the grid?
4. What percent of the electricity is generated locally and what percent is bought from the grid during normal operation?
5. Is the microgrid operated to peak shave and/or take advantage of the utility's time-of-use rate structure?

6. What DG and storage technologies are being used (type, how many, what sizes)?
7. How is the microgrid configured – is a schematic available?
8. Is there more than one bus?
9. Is there a separate bus for critical loads?
10. What control systems are used?
11. Is there a master control system that communicates with individual controllers on generators, storage, and loads?
12. Who makes the control systems?
13. Can the control system shed load/control loads?
14. Can the microgrid intentionally island?
15. Is a static transfer switch used?
16. How fast is the transfer when there is an event on the grid?
17. What modifications were made to standard control systems?

18. Overall, what are the advantages and disadvantages of this control system design?
19. Were any lessons learned during installation, adaptation, or operation that might be shared?
20. If you started over, what would you do the same or do differently?
21. Can you share information about equipment cost, control system cost, installation cost, or operations cost?

Appendix B. Supplemental Documentation

Documents are attached that provide additional project details.

- Rockwell Automation on Hyperion wastewater treatment plant (April 2003)
- Fort Bragg case study presentation (Encorp 2004)
- DTE microgrid capabilities brochure (December 2001)
- Mad River Park (Northern Power Systems 2003)
- Kohler Paralleling Switchgear Specification Sheet (January 2002)