Investigation of the Technical and Economic Feasibility of Micro-Grid-Based Power Systems

1003973

Final Report, December 2001

EPRI Project Manager
D. Herman

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

EPRI PEAC Corporation

ORDERING INFORMATION

Requests for copies of this report should be directed to the EPRI Distribution Center, 1355 Willow Way, Suite 2478, Concord, CA 94520, Pleasant Hill, CA 94523, (800) 313-3774.

CITATIONS

This report was prepared by

EPRI PEAC Corporation
942 Corridor Park Blvd.
Knoxville, Tennessee 37932

Principal Investigators
P. Barker
B. Johnson
A. Maitra

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Investigation of the Technical and Economic Feasibility of Micro-Grid-Based Power Systems, EPRI, Palo Alto, CA: 2001. 1003973.

REPORT SUMMARY

Background

Micro-grids are small power systems that can operate independently (as an island) with respect to the bulk power system. They are composed of distributed energy-production and energy-storage resources that are interconnected by a distribution system. They may operate in parallel with the bulk supply system during some conditions and transition to islanded (stand-alone) operation during abnormal conditions (such as an outage in the bulk supply or emergency). Micro-grids may also be created without a bulk supply connected at all, and so operate fulltime as an independent island. Potential micro-grid designs range in size from a single house operated independently up to large substation-scale systems that serve many feeders where total load may approach 100 MW. Micro-grids offer the potential for improvements in energy-delivery efficiency, reliability, power quality, and cost of operation as compared to traditional power systems. Micro-grids can also help overcome constraints in the development of new transmission capacity that are beginning to impact the power industry.

Objective

The objective of this report is to review the potential architectures, system engineering issues, and economic factors associated with the deployment of micro-grids as they relate to the technical and economic feasibility of such systems. Key issues include the type of system layout (network versus radial), operating voltage levels, types and capacity of generation required, and system protection and control needs. Another objective of the report is to identify areas of focus for future studies such as design approaches for new distribution systems and needed control and protection technologies to help facilitate development of micro-grids in the future.

Approach

The project team reviewed the history of the micro-grid, identifying that the early power industry actually began as micro-grids that transitioned to a centralized power system. The reasons for the transition to a centralized power system during the 20th century were reviewed. Today, there is new interest in returning to micro-grid approaches for some applications. This interest is brought about by the advent of new and improving distributed resource technologies, better control systems, the potential of micro-grids to improve system performance, and various constraints associated with continued expansion of the traditional bulk power system. The team determined that the new micro-grids of the 21st century can perform much better than the early 20th century micro-grids and may be competitive with traditional power system approaches. The project team investigated the layout and configurations that are possible for micro-grid architectures and reviewed the positive and negative issues associated with these systems, leading to recommendations for designs and future development efforts.

Results

Many examples of micro-grid systems were investigated. A small micro-grid with a fuel cell serving a cluster of six homes is discussed. The system includes an integrated fuel-cell package, protection and control, a bulk-system isolating device, fuel connection, and heat-recovery equipment for heat distribution to the homes. This system was found to offer reliability and efficiency benefits over a traditional distribution service. Another investigated system included a low-voltage network with numerous distributed generation sources and a “cellular” approach to islanded operation. The cellular approach enables separation into sub-grids as needed when parts of the grid were damaged, or it could consolidate into one large micro-grid. Perhaps one of the most interesting schemes considered was a lower-voltage DC micro-grid whereby power was distributed at 400 volts DC. The system employed inverters at each customer site. Strategic use of blocking diodes on the DC system helped with power quality and protection. One of the more interesting findings was that the use of uniformly distributed generation on micro-grids facilitates the ability to build distribution systems that do not need any high-voltage elements—they are entirely low-voltage. This low-voltage approach demonstrates potential for significant cost savings, power quality/reliability improvements, and provide improved safety benefits as well. It was determined that special controls and generator protection are required to facilitate proper operating of micro-grids. The present control methods being developed for conventional interconnection of distributed generation are not suitable for micro-grids.

EPRI Perspective

The rising interest in distributed resources (DR) has occurred due to improvements in generation technologies, power electronics, and the need for new capacity resources on the power system. The interest in micro-grids is really an outgrowth of the need to apply distributed resources in a manner that captures their potential value. A key potential benefit of DR is the ability to improve the reliability of the power system by providing emergency power during interruptions of the bulk system supply. This benefit can only be realized if the DR is operated in a configuration that facilitates islanded operation. Micro-grid approaches allow for this type of operation while also being able to capture all of the other benefits of DR such as waste-heat recovery, load reduction on the T&D system, and power quality improvements. Through this work, EPRI is enabling utilities to consider new options in the design and operation of power systems that can provide improved efficiency, the potential for ancillary services, improved reliability, and lower cost of operation.

Keywords

Micro-Grids
DC Micro-Grid
Power Quality Park
Power Quality and Reliability
Distributed Generation
Distributed Resources
Combined Heat and Power (CHP)

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Scope and Purpose of This Investigation

The micro-grid concept is a natural evolution of distributed resources that may be used to serve energy customers in areas where conventional power system approaches cannot satisfy the reliability needs. Micro-grids may also provide support to conventional power systems that are too constrained to meet the power demands of customers. This report reviews the potential architectures of micro-grids, the types of generation equipment that may be employed, application issues, costs, and potential benefits of such systems. It also evaluates innovative concepts that could be applied for the control of these systems. Recommendations are made for specific future research projects and hardware development that could bolster the success of future micro-grid systems.

What Is a Micro-Grid?

A *micro-grid* is a power system with distributed resources serving one or more customers that can operate as an *independent electrical island* from the bulk power system. Micro-grids may range in size from a tiny residential application involving the islanding of a single house up to small-city-size islands with 100 MW of total load. Micro-grids may operate fulltime independently from the bulk power system (and are never connected). Or, they may operate part-time in tandem with the bulk supply system during normal conditions but disconnect and operate as an independent island in the event of a bulk-supply failure or emergency.

Examples of some possible micro-grid applications include single customer sites, residential housing developments, college campuses, commercial/industrial office parks, and city-scale micro-grids serving thousands of customers. Micro-grids may offer the potential for lower total cost, greater efficiency, increased reliability, and increased security (compared to traditional approaches). Depending on the nature of the application, micro-grids may also employ environmentally benign generation sources such as fuel cells and renewable energy resources. Combined heat and power can be a key part of micro-grid systems and, in fact, would be one of the preferred modes of operation to obtain the best economics.

From an operational standpoint, the additional complexity of islanding multiple distributed generation resources on a section of the power system means that micro-grid architectures and control systems are different than those for conventional distributed generators operating on standard distribution systems. Conventional distributed generators operate in parallel with the bulk utility system and are protected from significant power disturbance by disconnecting from the power system. The protection and control of micro-grid generators will require that generators separate with a piece of the system (an island) and take on the responsibility for frequency regulation, voltage regulation, and sharing power production among the various sources included in that piece. For critical power applications, seamless transfer from the connected bulk supply to islanded mode is desirable to avoid disruptions of critical processes. This may require high-speed separation devices such as static switches.

Figure 1-1 is an example of a micro-grid system designed for a power quality park. It is composed of a variety of renewable and conventional generation sources and would be able to provide very high quality power to loads. This system operates during normal conditions as part of the macro-grid but separates during abnormal conditions as an islanded system. Due to the extensive use of static switches and other power-conditioning devices on this sample system, it would likely be more expensive than conventional-grade power, but hopefully less expensive than implementing individual power quality solutions at each facility.

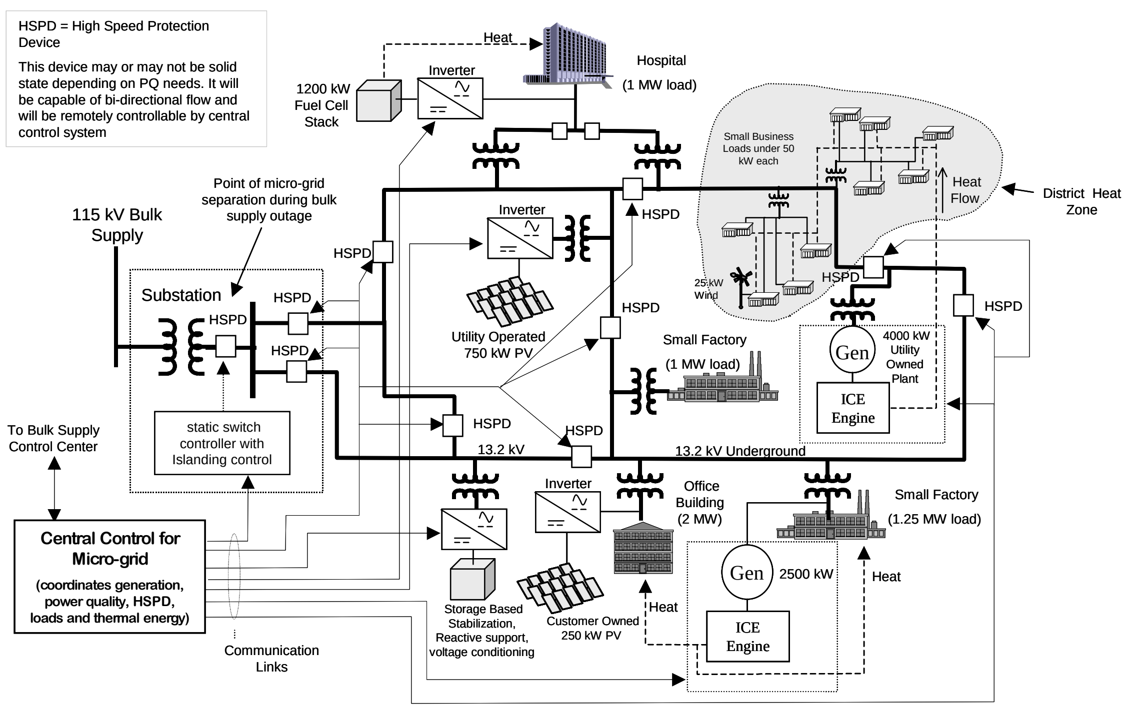

Figure 1-1
Example of a Micro-Grid Creating a Power Quality Park

Historical Perspective

The concept of the micro-grid, while receiving much attention today, is not a new idea. Rather, the micro-grid is a modern reformulation of the origins of the power system that Edison and the early electrical pioneers first created. The early power industry (1880 – 1910) began as what we would define today as DG systems implemented in micro-grid architectures. Of course, the terms “micro-grid” and “distributed generation” were not known back then. There was not even a large national grid to compare against at that time, so the concept of interconnected grid power was unknown.

The early power systems such as Edison's first Pearl Street station in New York City (circa 1882) served just a few blocks of the city, produced DC power, and had a total generating capacity of initially less than 1 MW (see Figure 1-2). Each "Jumbo Dynamo" (as Edison called them) shown in the figure was rated at 100 kW. By today's standards, this is right in the size range of distributed generation, and given the limited area served, the Pearl Street Station would certainly be classified as a micro-grid .

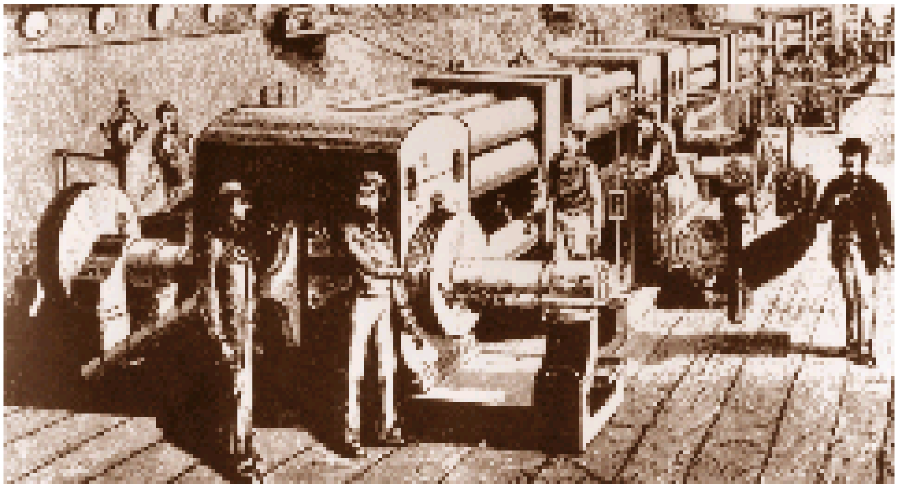

Figure 1-2
Edison's Pearl Street Station Entered Service in New York City in 1882 Serving a Small Part of the Financial District (Picture Courtesy of IEEE)

Micro-grids were the dominant form of electric power system during the first two decades of the twentieth century. In fact, as late as 1918 about half of the customers in the country (in most towns and small cities) were still receiving their power from small-scale isolated power systems with generation plants sized well under 10 MW in capacity. The areas served were less than a few square miles, and the power systems in individual towns were not interconnected with each other. Therefore each town operated as an independent island—a micro-grid. In addition to the small-town and city systems, smaller micro-grids composed of individual businesses such as hotels, industrial plants, and commercial offices often operated their own power systems, combining heat and power. Many of these installations distributed surplus energy (heat and electricity) to neighboring buildings.

Many early micro-grids were not particularly reliable because only one power plant supplied all of the energy. If that plant failed, then the whole system was down. Furthermore, many of the early power systems were devoted to lighting loads and only generated power at certain times of the day, such as the evening hours, because it was not economical to operate generators during periods of low usage. The cost of energy was often more than $1 per kWh when adjusted for inflation to current dollars (2001). The total energy efficiency of these early systems was reasonable when both heat and power were produced (which was the case for many locations where district heat was offered) but efficiency was often much less than 25% for early plants where waste heat was not used.

Early power system engineers considered interconnecting some of the systems to improve reliability. The idea was that if one town's power was out due to a problem at the plant, then the adjacent town would be available to pick up the load. It was also discovered that by interconnecting isolated systems, a greater diversity of load was obtained, which led to improved load factor and more economical operation of the generation plants. These concepts began to make people consider that isolated micro-grids should be interconnected into a larger system. In the early days, there was little standardization of frequency, and so many systems were not easily inter-connectable. Some systems were DC, and others were various frequencies between about 25 Hz and 100 Hz. Methods of synchronization, protection, and control of remote plants were also still in their infancy then, so this was a barrier to interconnection as well.

Between 1910 and 1920, various technological innovations and other factors set in motion the movement away from the early micro-grids and toward a system based upon increasingly larger-scale central-station plants interconnected via transmission lines. Now cities and towns could be interconnected, and power could be shared between areas. During this period, transmission voltages as high as 150 kV were being introduced, and so relatively large amounts of power could now be transmitted efficiently over significant distances.

The factors that led to the preference of a centralized large-area grids as opposed to the early micro-grids were as follows:

- Developments of large-scale hydro-electric resources located significant distances from urban load centers required the utilization of transmission lines to bring this power to urban areas, which encouraged the development transmission and distribution (T&D) networks
- Newly developed T&D technologies during this period were improving the reliability and economics of delivering and distributing power over large distances
- Increasing use of standardized 60-Hz frequency made interconnection of various separately powered areas possible
- Steam and hydroelectric power plants of the time had significant economies of scale, so larger plants could be built and operated at a lower cost per kilowatt of capacity and lower cost per kilowatt-hour of energy this is still true for many energy-production technologies today
- Aggregation of many generators and a large diversity of load on a single large grid, as opposed to many small micro-grids, offered improved load factor, an improved ability to dispatch the most efficient generation, and availability of generation to meet demands. These benefits, it was felt, translated into lower cost and greater reliability compared to the early micro-grids.

In addition to the above technical and economic factors, the government also played a role in the switch to centralized power systems. Especially during the period from 1907 up to the early 1970s, public policy and legislation encouraged the movement to larger centralized systems. Examples of favorable public policy to centralized systems during the twentieth century include:

- **Utility Regulation:** Formation of state and federal regulatory agencies that encouraged the formation of large regional utility companies made if difficult for small power produces to sell power to adjacent customers
- **Government Financial Support of Large-Scale Generation:** Major power projects were constructed in the 1920 – 1960 era, which further increased the scale of power plants and need for transmission (examples include Hoover dam, Grand Coulee dam, TVA, and various nuclear power projects). In the 1950 – 1979 era, the development of nuclear power followed in the footsteps of hydro projects.
- **Rural Electrification Administration:** This policy to interconnect farms and rural areas to the centralized system by subsidizing the extension of power lines into these regions hurt the development of other alternative sources that were micro-grid-based

These technical, economic, and political factors led to the eventual demise of the early micro-grid systems. By the 1970s, more than 95% of all electric power being sold in the U.S. was through large centralized power systems. Despite this, various niche uses of micro-grids remain today, including:

- Power supplies for geographic islands where undersea cables cannot reach the island
- Power supplies for remote communities in locations without a transmission connection to the bulk power system and where construction costs of such an extension are prohibitive due to the distance or a physical barrier, such as a mountain range or river
- Applications with bulk system access where, despite such access, end users have decided to self-generate and island themselves for various reasons
- Power quality and reliability applications at some industrial and commercial end users that operate onsite generation and run as an island during interruptions of the utility system

The evolution of the power system from a highly decentralized micro-grid-based system in 1910 to the large-scale grid of today occurred over a half-century period and is shown qualitatively in Figure 1-3. The evolution begins with a fully decentralized system, meaning that the load is 100% powered by micro-grids and/or distributed generation. During the last three decades of the twentieth century, various factors have increased interest in the use of distributed generation and in perhaps returning to the more widespread use of micro-grids. These include the energy crisis of the 1970s that resulted in the Public Utilities Regulatory Policy Act (PURPA) in 1978. PURPA was designed to encourage alternative energy sources. Also, technical improvements in distributed generation (DG) technologies during the 1980s and 1990s, the need for increasing reliability/power quality in power systems, deregulation of the power industry, and an increasingly constrained T&D system have promoted distributed generation.

To a certain extent, there is already a slight decrease in the amount of centralization of the system as more DG is brought online (although this is difficult to quantify). The key questions for the future are “How much will the use of distributed generation grow?” and “Will micro-grids play a major role?” There are several possible paths that society can take in this regard, ranging from little change from the present energy production/delivery methods to a wholesale reconstruction of the power system with widespread distributed generation and use of micro-grids. The factors that will determine the direction taken are economic, political, and technical. This report reviews these factors, but it is too early to determine which direction will prove most viable for society.

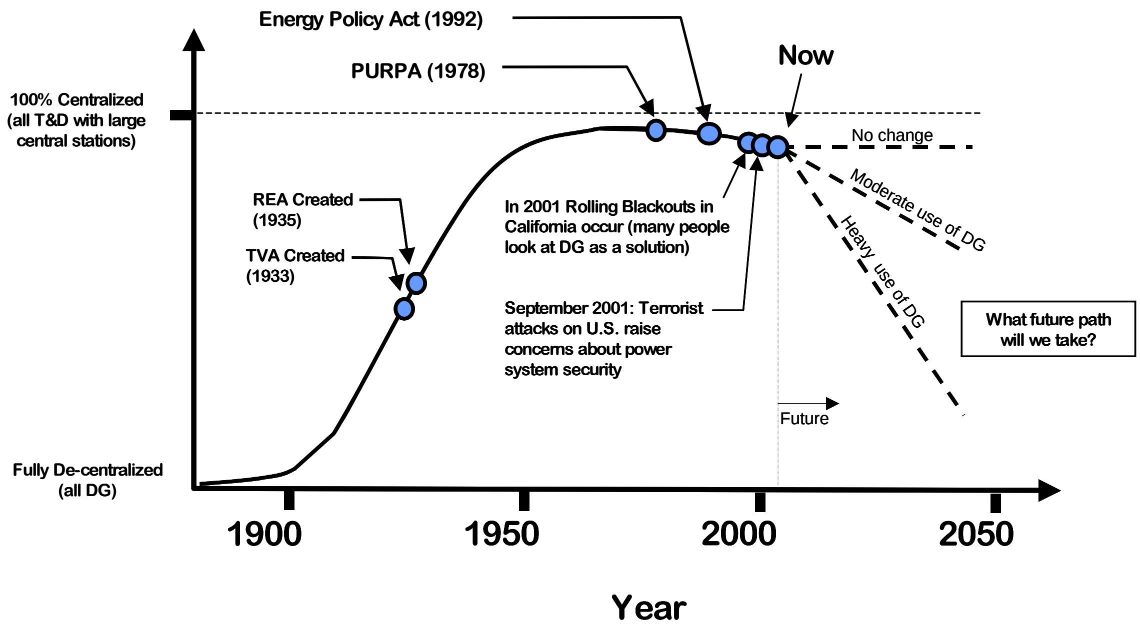

Figure 1-3
Degree of Centralization of the U.S. Power System

Why Use Micro-Grids Today and In the Future?

The demise of early micro-grids during the first part of the twentieth century does not mean that they cannot once again play a role in our future electric power system. There have been significant changes in technology, regulatory policy, and customer end-use energy needs over the past 30 years that have come together to increase the potential value of distributed generation and micro-grids. Today, we may be at a threshold where widespread use of micro-grids can be both technically and economically viable compared to traditional central-station approaches.

The potential use of micro-grids is tied to the strong current interest in distributed generation. Some reasons for increased interest in DG include:

- **Cost of Transmission and Distribution:** The difficulty of building a new transmission and substation infrastructure has become high in some areas due to permitting issues, public resistance to the construction of new lines, and the difficulty/cost of upgrading or building new infrastructure in many urban areas. Distributed generation may be able to be brought online faster and at a lower cost than conventional capacity, solving some of the short-term capacity constraints that are arising in current electricity markets.
- **Better DG Technologies:** Emerging products such as fuel cells and micro-turbines offer new opportunities for distributed generation. The cost of renewable forms of distributed generation such as wind turbines and photovoltaic sources has dropped significantly, while

performance has improved significantly during the past decade. Continued further improvements are occurring rapidly. New DG technologies offer energy security and no emissions. Furthermore, the cost of more traditional forms of distributed generation, such as internal combustion engines and small combustion turbines, has declined due to technology improvements and increased scale of production.

- **Power Quality and Reliability:** The need for high reliability and good power quality has increased as more customers install microprocessor-based devices and sensitive end-use machines. DG can offer significant improvements in both of these areas.
- **Power Electronics Revolution:** New power-conditioning and control technologies brought about by the power electronics revolution are making possible improved inverters (needed for DC sources) and better means of integrating and controlling DG that is operated on distribution systems.
- **Public Policy:** In a full reversal from the past, public policy today is favoring distributed generation that offers improved efficiency, lower emissions, enhanced power-system security, and other benefits of national interest. The polices that support this include tax credits for renewable energy, standards for power generation portfolios that require a certain amount of renewable energy production, emissions restrictions, net metering, and various other policies.
- **More Knowledgeable Energy Users:** Energy users are becoming more aware of alternative power approaches and are more willing to consider onsite generation options than just a few years ago. Many are interested in combined heat and power as well as reliability enhancements.

For the above reasons, there is a movement toward distributed generation that is just gathering steam at this point. As DG utilization increases, a natural evolution of this trend will be to implement DG within a micro-grid framework that can potentially solve some of the T&D system constraints that the industry is facing today while also enhancing the local reliability. A *well-designed and applied* DG installation in micro-grid format may offer lower cost, higher reliability, and lower emissions than some conventional-source scenarios.

The key phrase is “well designed and applied.” Poorly applied and designed systems may actually have lower efficiency, lower reliability, higher emissions, and higher costs than conventional utility-system scenarios. Even a good design cannot necessarily improve on the cost of some of the lower-cost utility markets. The existing T&D system is remarkably efficient (about 90% at delivering power), it provides very high reliability (better than 0.999 at almost all sites), and is fairly cost-effective (power is sold to customers at less than 10 cents per kilowatt-hour at most locations). Beating these performance figures with distributed generation in micro-grid architectures is difficult unless the application uses the correct form of generation and is carefully designed to squeeze out other benefits such as combined heat and power (CHP) or reliability. Without these benefits, many micro-grid applications will not offer more value than their T&D counterparts at current prices for DG equipment.

Modern Micro-Grid versus Early 20th-Century Micro-Grid

Modern micro-grids will be somewhat different than their early 20th-century counterparts. Most early 20th-century systems consisted of a central power plant with radial feeds, which perhaps covered a few square kilometers. They were not designed to interconnect with any sort of bulk power system, and their controls and protection were limited to simple fuses and fairly basic relaying functions. Modern micro-grids will be designed to operate with a variety of DG sources interconnected at various points located all over the grid. They will likely employ a central-control system that can coordinate multiple generator locations on the grid to ensure good dispatch and balance (sharing) of generation that facilitates best-case economic operating conditions.

Modern micro-grids may at times operate in parallel with the bulk supply system and at other times operate independently. Therefore, the controls, protection, and design of the system will be capable of handling both modes of operation. Modern micro-grids will employ extensive use of communications between generators and various control devices. Communications with the bulk power system may be needed to facilitate separation and reconnection of the micro-grid to the bulk system. Modern micro-grids will be designed to provide high power quality and reliability for customers. As a result, many will employ looped architectures to allow redundant feeds to all major grid locations and will also employ advanced power-conditioning technologies to help minimize voltage sags, interruptions, voltage fluctuations, harmonics, and other power quality anomalies. Where possible, modern micro-grids will employ CHP, just like the early ones, because of the improved economics.

Micro-Grid Stakeholders

Who will own and operate micro-grids? The answer to this question is that all participants in the energy production, delivery, and end-use sectors will have an interest in owning, operating, or being involved with micro-grids. Vertically integrated utilities, energy-service companies, or wires companies may own or operate micro-grids that are configured as power quality or multi-energy business parks where electricity, power reliability, and thermal energy (via CHP) will be products that are sold to the tenants as *value-added services* within those parks. Individual electric customers may install their own micro-grids to obtain these services directly. End users who employ micro-grids may range from a single residence (really just an off-grid house) up to a factory campus with multiple buildings spread out over a large area.

On a larger scale, the federal government, state regulatory agencies, and regional transmission organizations could have a strong interest in seeing micro-grids implemented for national security and reliability of bulk systems. As an example, for the purposes of the reliability of bulk power systems, various distribution substations could be configured as feeder-level micro-grids to break off as needed from the main system during a reliability crisis in the bulk system. These islanded distribution systems could continue to serve loads with local generation and could reconnect once the crisis has ended. This type of system breakup is not much different from conventional emergency load shedding from the point of view of the bulk system. The exception is that areas disconnected are not without power but continue to operate as micro-grids. Micro-grids could also “export” power back into the bulk system at appropriate times, depending on bulk-system needs and the price offered.

2
EVALUATION OF POTENTIAL MICRO-GRID ARCHITECTURES

Overview

There are many possible configurations for micro-grids, ranging from very small systems serving a single customer site up to very large systems that serve thousands of customers. This chapter investigates possible architectures for micro-grids and discusses some of the factors that must be considered in the design of such systems.

In selecting a suitable micro-grid architecture, some key design elements will include:

- Number of customers served
- Full time or part time micro-grid?
- Physical length of circuits and types of loads to be served
- Voltage levels to be used
- Feeder configuration (looped, networked, radial, and so on)
- Types of distributed generation utilized
- AC or DC micro-grid
- Heat-recovery options
- Desired power quality and reliability levels
- Methods of control and protection

With regard to the above characteristics, there is no one particular system design that can be universally applied to all micro-grids. The variety of loads to be served, intended applications, generation technologies to be applied, and environments in which these system will be located dictate that micro-grid designs will be very diverse.

Micro-Grid Service Areas

Micro-grids may be applied in a broad range of sizes and configurations. Shown in Figure 2-1 are examples of possible micro-grid "subsets" that could be derived on a typical radial distribution system. These micro-grid subsets include a single customer, a group of customers, an entire feeder, or a complete substation with multiple feeders. A very large substation could have up to 100 MW of capacity, eight or more feeders, and could be serving more than 10,000 customers. When islanded, such stations would represent the high end of the micro-grid size range.

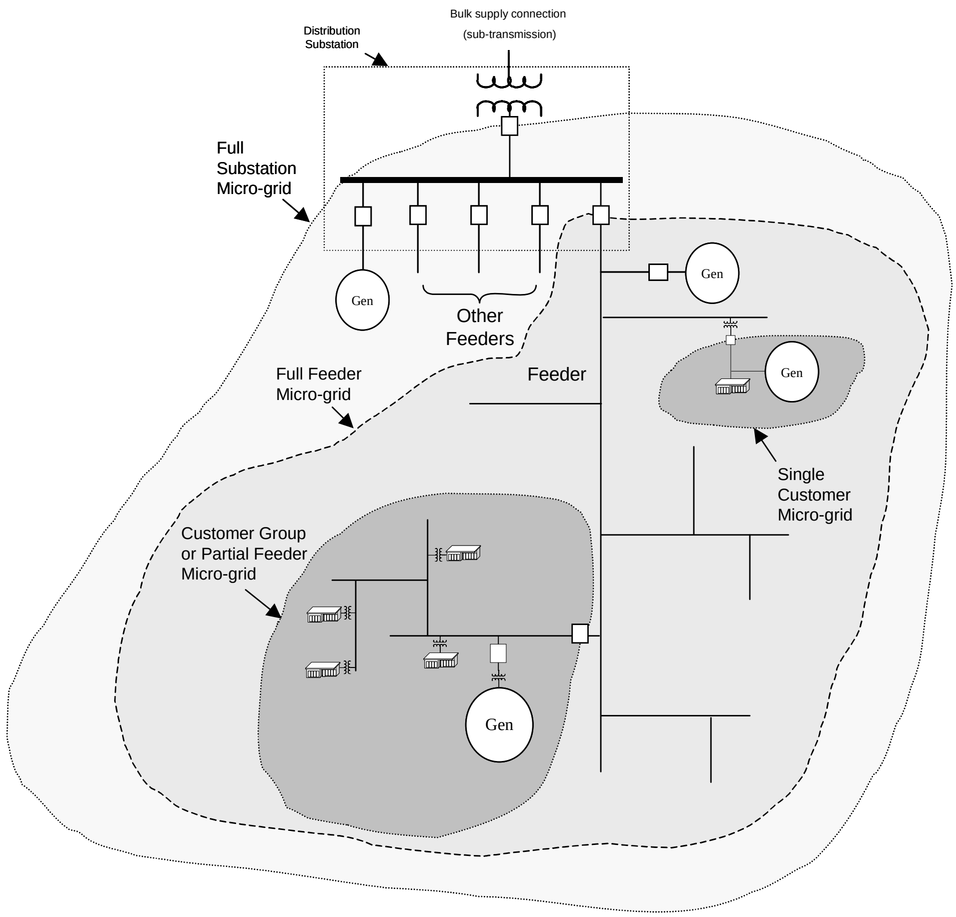

Figure 2-1
Examples of Micro-Grids Oon a Radial Distribution System – From Single Customer Up to Entire Substation

Micro-grids employed on radial circuits are not the only possibility. Micro-grids may be employed within looped or networked architectures. In fact, for reasons of reliability and control flexibility, if a system were designed from scratch and were intended for high reliability, it would likely employ a looped or network architecture. This would allow redundant power flow paths between generation sources and loads, and improved voltage regulation.

Micro-grids, regardless of their size, must take on key control responsibilities while operating in the islanded state. While the generation is operating as an island, the generator should be able to provide adequate voltage and frequency control, suitable harmonic levels, the ability to load follow, and adequate reactive power for loads. For closed transition transfer or parallel operation with the utility system, the generator must be able to properly synchronize with the main utility system prior to connecting with the system and picking up load. Otherwise, serious damage may result. The generator must not adversely impact reliability, voltage regulation, or power quality on the bulk power system while the micro-grid is connected to it.

Given the wide range of possible configurations for both radial and networked micro-grids, the following pages present a variety of designs ranging from the single-customer configuration up to large substation-scale systems. Some of these systems are already in use today, and others are hypothetical examples of future systems that could be deployed once the key technology elements are in place.

Single-Customer Micro-Grid

The single-customer micro-grid is the most basic form of the micro-grid. It has already seen widespread utilization in various industrial, commercial, and residential applications for reliability purposes. The simplest and least evolved version is a basic backup generator with a transfer switch. With this type of installation, the backup generator is started and the load is transferred to the generator by the operation of a transfer switch (see Figure 2-2). Depending on the situation, the transition may be by a closed transition (momentarily operating in parallel with the utility system) or by an open transition that causes a brief interruption of power. This configuration can be used to transfer some or all of the load to local generation and provide a reduction in loading on the bulk supply system. The most common usage is simply as standby (emergency) power to keep the load energized when an outage in the bulk supply. Standby generation is not “true” distributed generation, as it operates only at times of a system emergency and is usually not operated daily for system support purposes. Nonetheless, it is a good example of a primitive micro-grid.

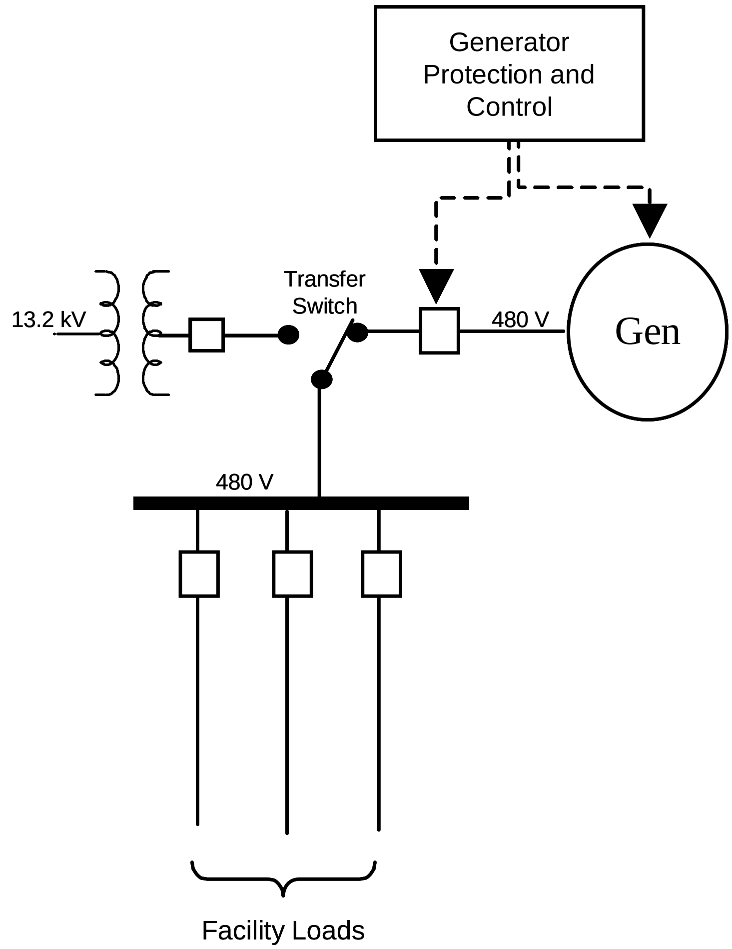

Figure 2-2
The Most Basic Form of a Micro-Grid – A Standby Generator with a Transfer Switch (Shown Operating as an Island)

The system shown in Figure 2-2 operates by manual movement of the switch, or automatically by detection of a power interruption on the utility system, which initiates operation of the switch. This standby generation configuration, as it is usually implemented, does not facilitate "seamless" transfer from the bulk-system to islanded mode during utility-system power interruptions and is not capable of safely operating in parallel with the bulk power system for any length of time because it lacks some of the needed key protection controls. For safe and successful parallel operation with the bulk supply system, a generator must be equipped with appropriate island-detection circuits and must be properly designed and operated from the perspective of grounding, power-system protection, synchronization, reactive control, and other operating issues. A system such as the one shown in Figure 2-3 provides these capabilities to allow for parallel operation with the power system and islanded operation during power interruptions of the utility system. This type of system can provide true DG capability by operating for extended periods in parallel with the utility system and may peak-shave the load or even export power, depending on the application.

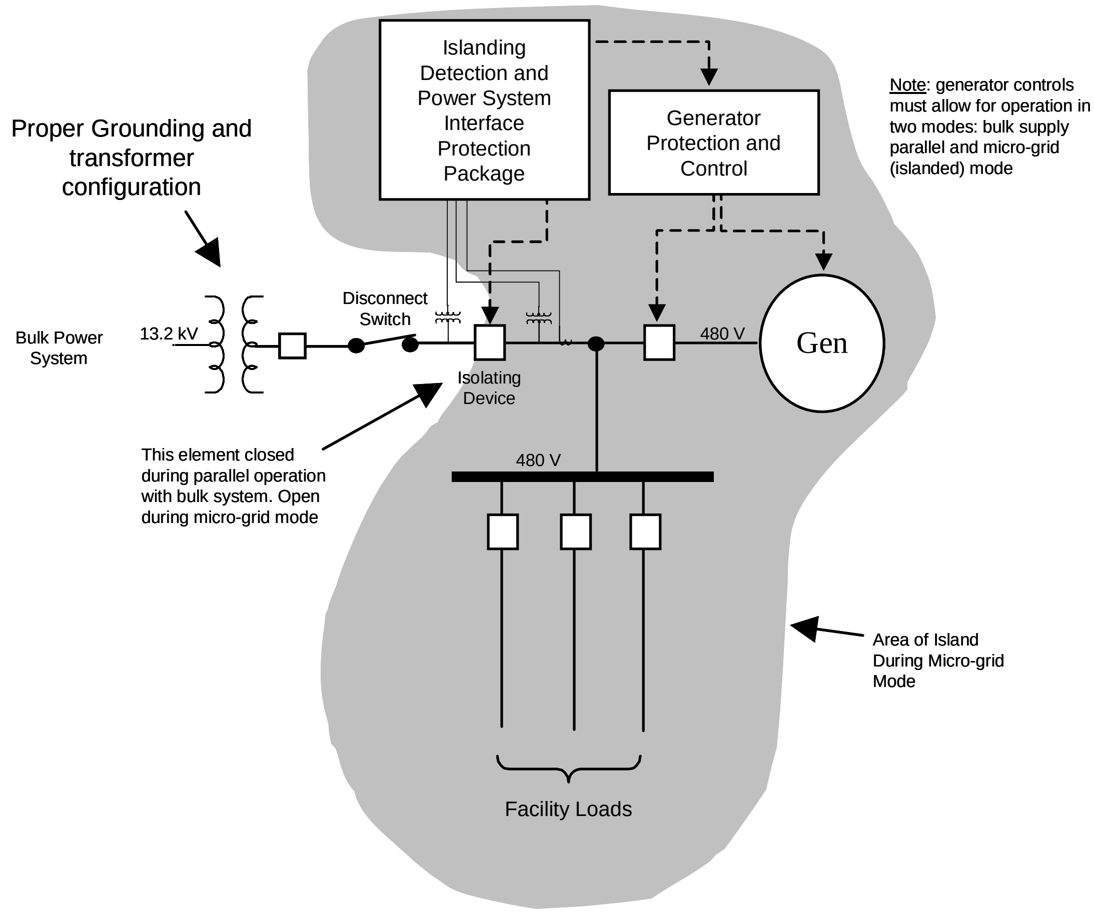

Figure 2-3
The Single Customer Micro-Grid with Proper Protection to Facilitate Both Parallel and Islanded Operation

The system in Figure 2-3 is still relatively simple, but more advanced single-customer micro-grid systems can include combined heat and power and high-speed switching devices (static switches) that can help ensure a seamless transition from bulk-system-parallel mode to micro-grid mode.

Figure 2-4 is an example of an advanced single-customer micro-grid employing fuel cells, heat recovery, and energy storage. It provides the capability to operate in parallel with the utility system for grid support during normal conditions. The circuit breaker that serves as the isolating device between the utility system and the micro-grid can be a mechanical device that operates in a few cycles, or it can be a static switch device that could isolate the system in about ½ cycle, performing essentially a seamless transfer during utility-system voltage sags. Use of the waste heat from the fuel cell helps to raise the total energy efficiency of the generation system to nearly 90% in ideal cases. Energy storage on the DC bus helps the unit load follow and handle transient load steps. The master controller coordinates the entire system and may be programmed to follow heating needs by modulating electrical generation in some applications.

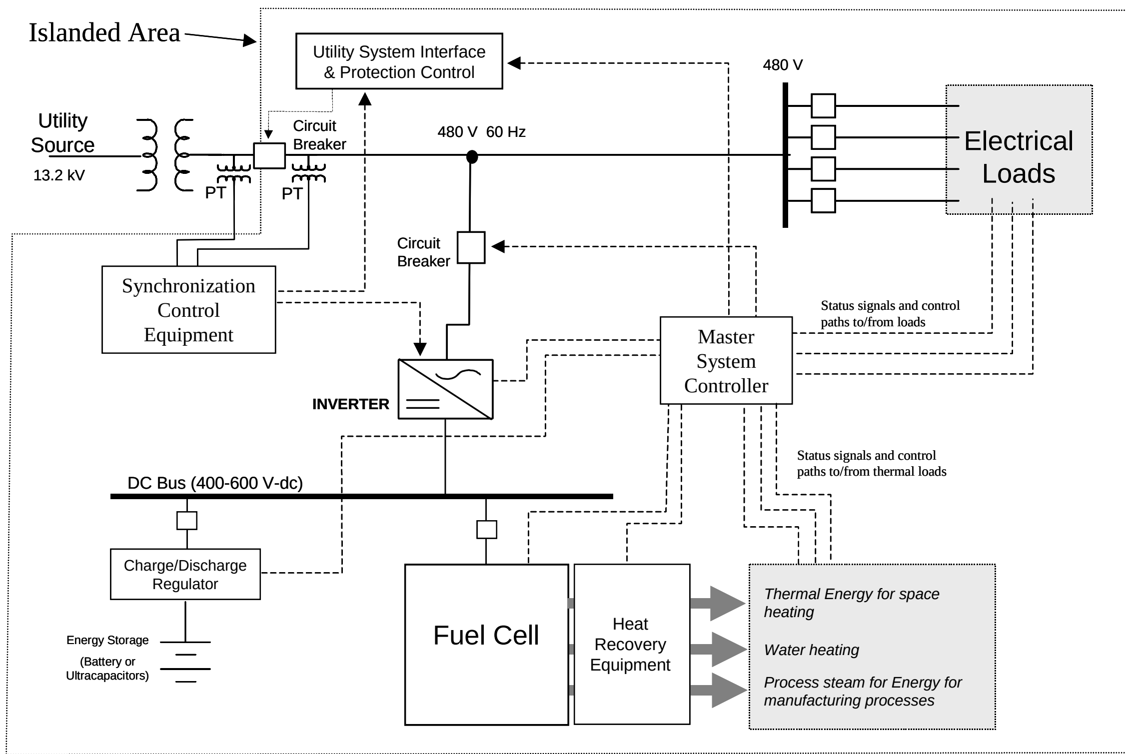

Figure 2-4
More Advanced Single-Customer Micro-Grid with Heat Recovery

Radial Customer Group and Micro-Grid for a Business Park

A group of customers served on a radial system may be islanded to create a micro-grid. The simplest type of radial multi-customer micro-grid is one where a single generation site supplies all of the power for the micro-grid. Figure 2-5 is an example of a fuel-cell-based micro-grid employing a single 50-kVA fuel cell serving six homes. In this case, the secondary system is "islanded" by opening the isolating device. Waste heat of the fuel cell is employed for heating purposes, and there is utilization of thermal and electrical energy storage. Short-term electrical storage helps to provide stability and load-following capability in islanded mode. Thermal storage (several hours' worth of thermal-energy capacity) helps match thermal-energy availability with electrical demand. In this concept, all of the equipment required for the six-home micro-grid could be packaged in a suitable equipment enclosure located at the distribution transformer that serves that customer cluster. During utility system outages, the customer cluster would continue to operate as an island.

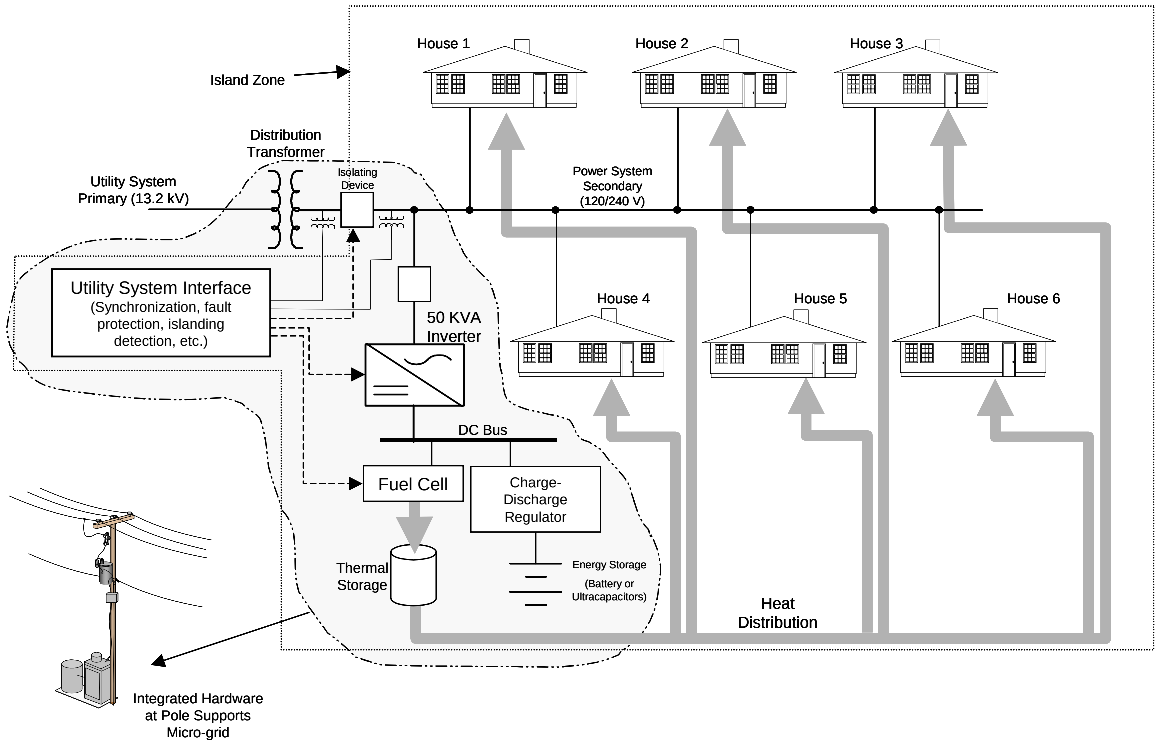

Figure 2-5
Example of a Six-Home Micro-Grid Served by a Single Fuel-Cell System

This type of configuration has a minimal amount of control requirements and has no issues with load sharing of multiple generation units because it employs only a single source. This architecture could be employed for residential, commercial, or industrial micro-grids supplied by a single source on secondary (low-voltage) radial power systems. Use of a mechanical breaker or contactor as the isolating device could allow a relatively fast but not quite seamless transfer from grid-parallel to islanded mode. Use of a static switch with appropriate high-speed power quality-based triggering of the switching function would ensure a very rapid response (within 1/2 cycle). The integrated package of equipment at the distribution transformer might be owned by the utility company and provide all of the support for the micro-grid, all within the framework of a low-voltage interface. In addition, homes are close enough for easy and efficient distribution of waste heat, and the size of the grid, which would have six or more customers, ensures a much better load diversity than is possible serving just a single customer. This would lead to improved system economics by allowing a more optimally sized generation package.

Larger versions of this radial type of micro-grid are possible to serve significantly sized businesses, college campuses, and other facilities, as shown in Figure 2-6. These would employ standard designs of radial distribution systems and be supplied with energy by a single generating plant with sufficient capacity to carry the campus load when it is islanded as a micro-grid. Multiple generators operating in parallel with suitable paralleling switchgear and controls would normally be employed in such situations. This allows the generation to be dispatched based on demand and also provides some redundancy in the event of a loss of one generator unit. The architecture shown in the figure is also similar to the architecture that would be used for a full radial-feeder micro-grid with a single source.

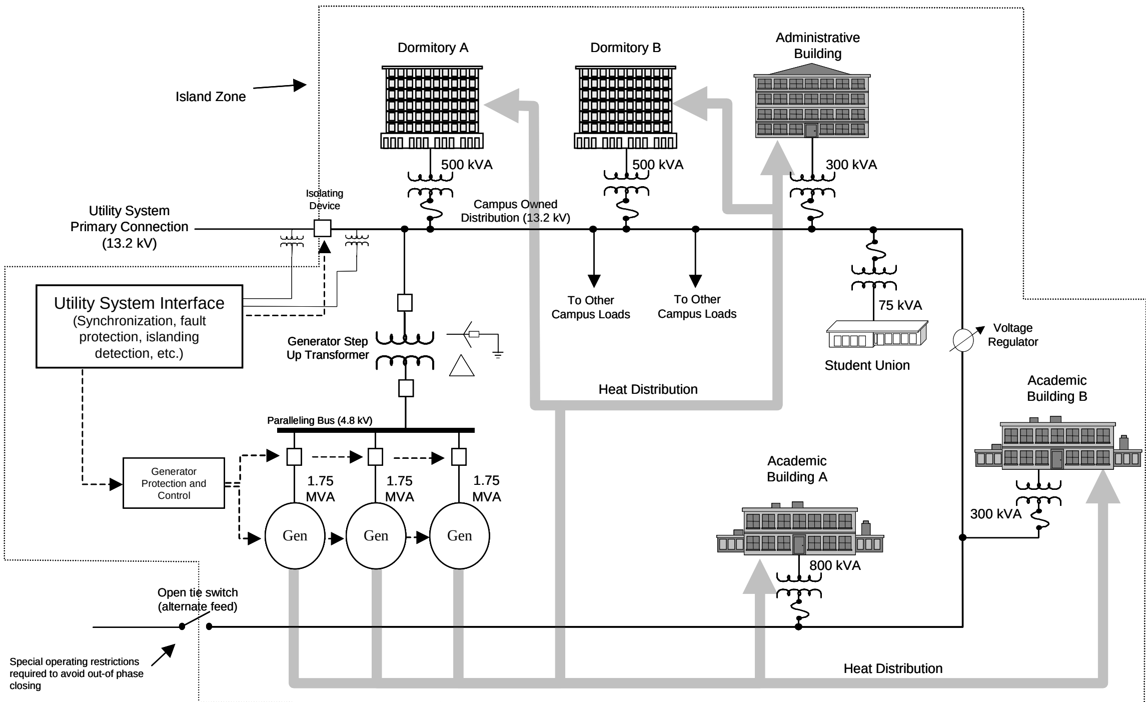

Figure 2-6
Example of a Radial Business Park or Campus -Based Micro-Grid

Full Substation -Based Micro-Grid

An entire substation may be configured to act as a micro-grid. The “full substation” micro-grid, shown in Figure 2-7, is an example of a two-transformer eight-feeder substation with a split-bus design. The station is configured with two generators supplying each bus of four feeders. An *isolating device* that can separate the bulk system supply from each bus serves as the island demarcation point. The isolating device may be either a static switch or a conventional mechanical device such as a circuit breaker, depending on the power quality requirements of the application.

When used for high quality power applications where a seamless transfer to “islanded mode” is required during transmission voltage sags or power interruptions, high-power inverters with short-duration energy storage can be used to support the load until the generation can be adjusted to the proper output level. The inverters can also be used to help stabilize the micro-grid voltage and frequency during islanded and transitional operation. The bus tie switch in Figure 2-7 between Bus (A) and Bus (B) may be closed to facilitate support of both buses from either substation transformer or from either set of generators. A master controller coordinates the generation and all switchgear to facilitate operation in various modes and contingency conditions, such as loss of a generator.

Load shedding can be performed to ensure that at least some feeder loads can be carried during partial generator failures. Load shedding also facilitates the ability to use generators rated at less than the total load on the bus if it is desirable to not carry all feeders at once. Of course, this configuration may operate in parallel with the bulk system supply under normal conditions or as a separate island during outages in the bulk supply power or during special conditions. The micro-grid shown in Figure 2-7 was intended for radial feeders but will also work supplying low-voltage network feeders, assuming that all feeds emanate from the same substation bus. This design might also be used for new stations that have no transmission connection at all—they simply run fulltime as micro-grids. These “transmissionless” stations could be deployed in transmission-constrained areas that have good availability of natural gas. Combustion turbines and internal combustion engines can be used for generation in present-day applications, and larger-scale fuel cells could be used in the future.

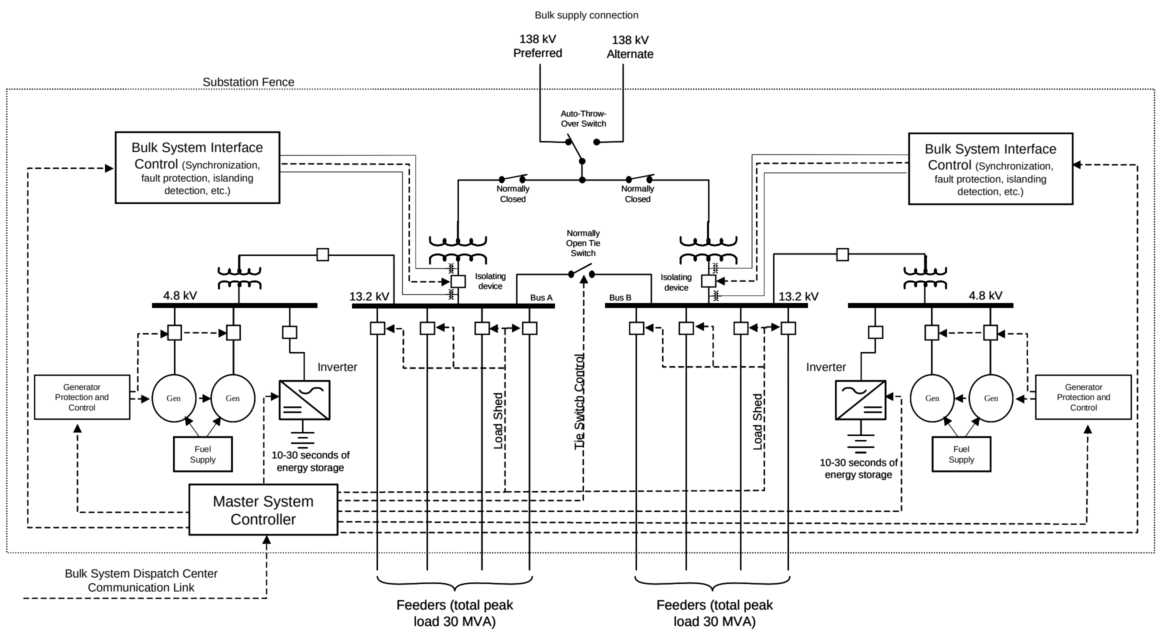

Figure 2-7
A Full Substation Micro-Grid System with Generation Located at the Substation

Micro-Grids Operating with Multiple Dispersed Resources

The micro-grid architectures discussed so far have been single-source systems where generation is located at a single point, such as at the substation. However, there is considerable interest in developing micro-grids with multiple generators at widely dispersed locations and with a variety of generation types, including various combinations of solar, wind, fuel cell, reciprocating engine, combustion turbines, and energy-storage devices.

The use of multiple generators at dispersed locations requires a significant change in the protection and control methodologies compared to those with a single generation plant. No longer will the standard radial protection and relaying approaches be appropriate, and the generators must communicate with each other in a manner that ensures adequate load sharing, system stability, proper frequency and voltage control, and optimal system performance regarding efficiency and cost of energy production.

Figure 2-8 shows an example of a micro-grid employed on a radial campus distribution system. The system primary voltage is 13.2 kV. The peak load on the micro-grid area is 2975 kW, and generation capacity is 3000 kW of dispatchable internal combustion engine (ICE) units and 150 kW of intermittent renewable resources. The *bulk system isolating device* shown in Figure 2-8 is responsible for separating the campus system from the bulk utility system. A sectionalizing switch further down the feeder provides the ability to break the micro-grid apart into two smaller micro-grids, which provides added reliability if one section of the campus becomes faulted or if one of the generation plants is unavailable. The closing of the sectionalizing switch is blocked unless proper synchronization between the grids is achieved or unless override from the master controller indicates a need to close. The master controller monitors loads, voltage, and frequency, and adjusts the generators and switching devices accordingly to ensure proper load sharing and optimal economic dispatch. The ICE units are operated as synchronous voltage sources, adjusting their excitation levels to regulate voltage on the system.

The renewable resources are controlled as current sources and represent about 5% of the system capacity in this example. They must not be too large relative to total system capacity. Otherwise, a loss of system control may occur. The energy-storage device provides a few seconds of energy storage to an inverter that is programmed to function as a power-conditioning device that stabilizes the voltage and frequency of the system during large load steps. Load shedding (not shown) could be added to improve the ability of the micro-grid to ride through various contingencies, such as a loss of a generator.

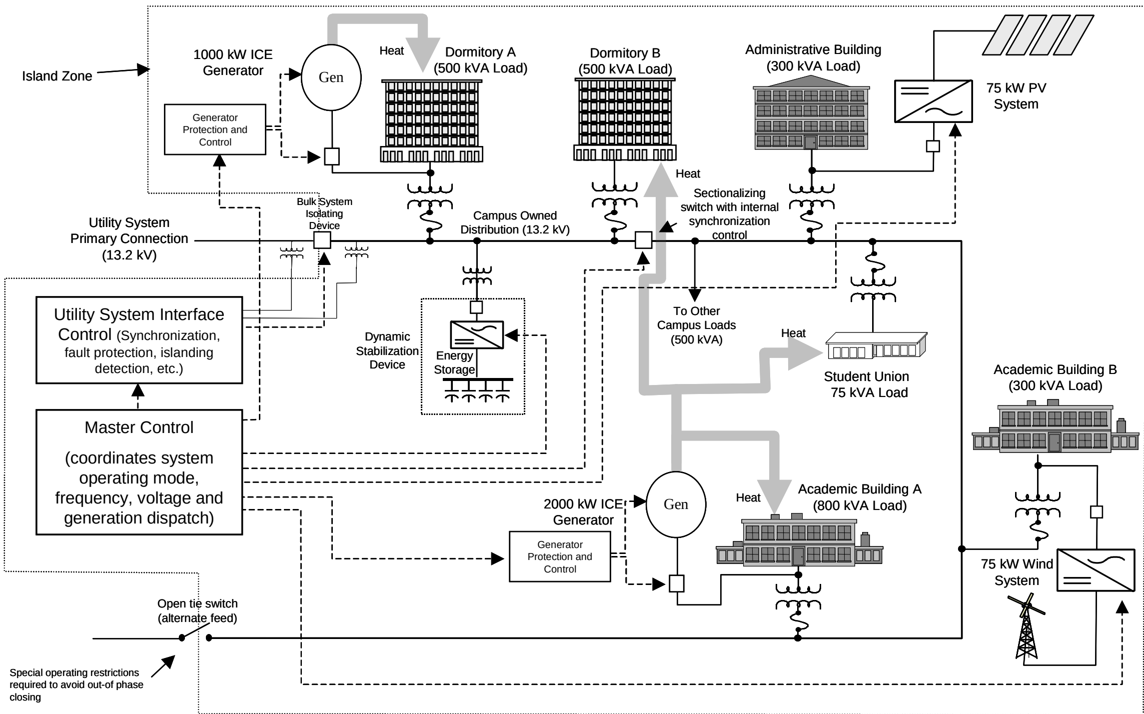

Figure 2-8
A Conventional Radial Campus Distribution System Converted to a Micro-Grid

The campus micro-grid of Figure 2-8 could operate in parallel and independently from the bulk utility supply. Normally, it would operate in parallel but would separate during emergencies or interruptions of the utility supply. Depending on the length of the feeder, voltage-regulation devices (such as step-voltage regulators) might be needed on the feeder. If these devices are used, they would need to employ regulator controls capable of responding properly to bi-directional power flow. Note also that the open tie switch located at lower left of Figure 2-8 is meant for emergency backfeed, but has not been equipped with synchronization equipment. Without synchronization, it could only be used when both the normal utility feed and the micro-grid generation were disabled and it was being closed into a dead feeder.

Adaptable Micro-Grid That Breaks Into Sub-Grids

In studying the architecture of Figure 2-8, it is clear that micro-grids could be subdivided into many smaller micro-grids (or sub-micro-grids) if the proper switching devices, generation controls, and generator locations are employed. Figure 2-9 shows a looped primary feeder that can be broken into four sub-grids or recombined into a single larger micro-grid as needed. The keys to proper functioning of this architecture are:

- The use of sectionalizing switches that have synchronizing capability (they only close when voltage magnitude, phase angle, and frequency differences on both sides are nearly equal)
- The use of individual sub-grid controllers that can adapt to various modes of operation as the sectionalizing switches change state

The sectionalizing switches would also need to be able to close into “dead” (de-energized) areas if generation is disabled in those areas and it is desirable for an adjacent sub-grid to attempt to carry a load on a dead sub-grid. Communication between the various sub-grid controllers, generators, and switching devices is required to facilitate proper load sharing among generators and good voltage/frequency control on the system. For each possible combination of sub-grids, there would need to be a single controller that can take charge of the system. Which controller is in charge could change, depending on the state of the system and number of sub-grids that are operating in parallel. A single connection point in the bulk utility supply is shown in Figure 2-9, but other arrangements could allow for multiple connection points if desired.

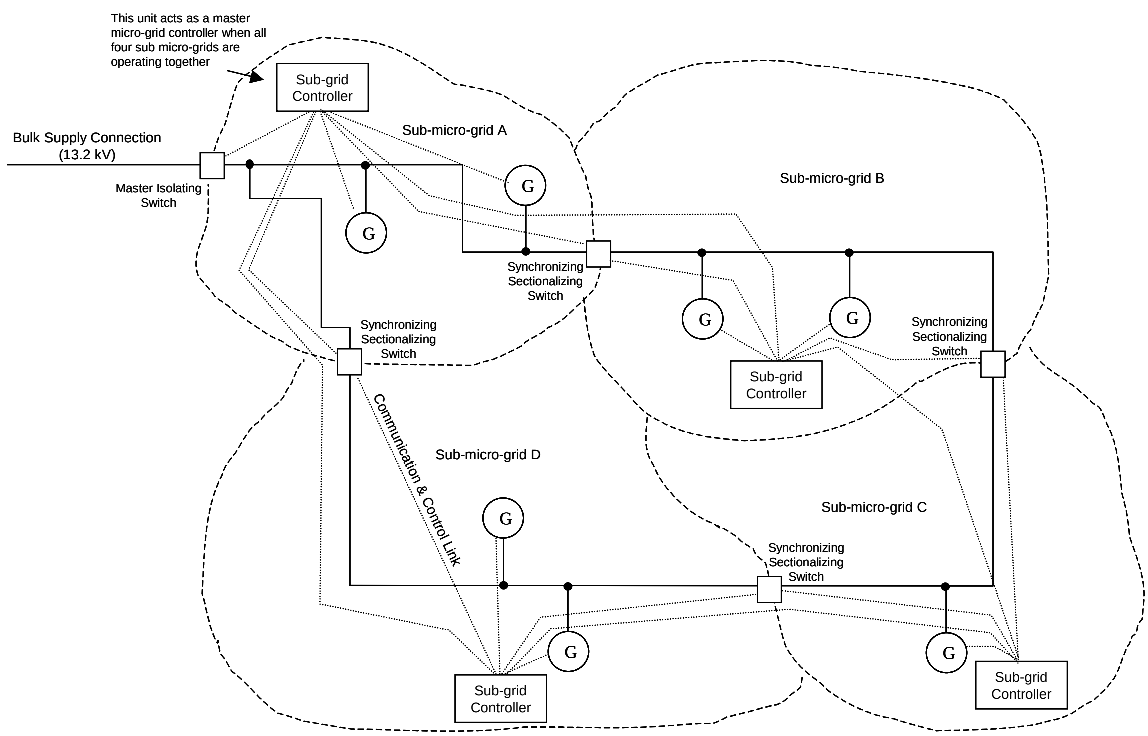

Figure 2-9
A Micro-Grid Configured to Break Apart into Numerous Sub-Grids

Networked Primary Micro-Grid Operating in a Power Quality Business Park

A very evolved form of the micro-grid is the *networked primary PQ business park*, shown in Figure 2-10. It is composed of a variety of renewable and conventional generation sources and has a networked primary. With the extensive use of high-speed switching devices (most likely static switches), inverter-based power-conditioning equipment, and redundant power flow paths, it can provide a higher level of reliability and power quality than either a conventional distribution system or a radial micro-grid configuration. Although such systems will likely be more expensive than conventional systems, they can, if properly designed, be less expensive than implementing individual power quality solutions at each facility. Protection and control will be particularly complex and similar to that on a transmission system. This type of micro-grid makes the most sense in suburban business parks that need very high reliability. In some areas, a low-voltage network approach may be more appropriate, depending on load density (see next section).

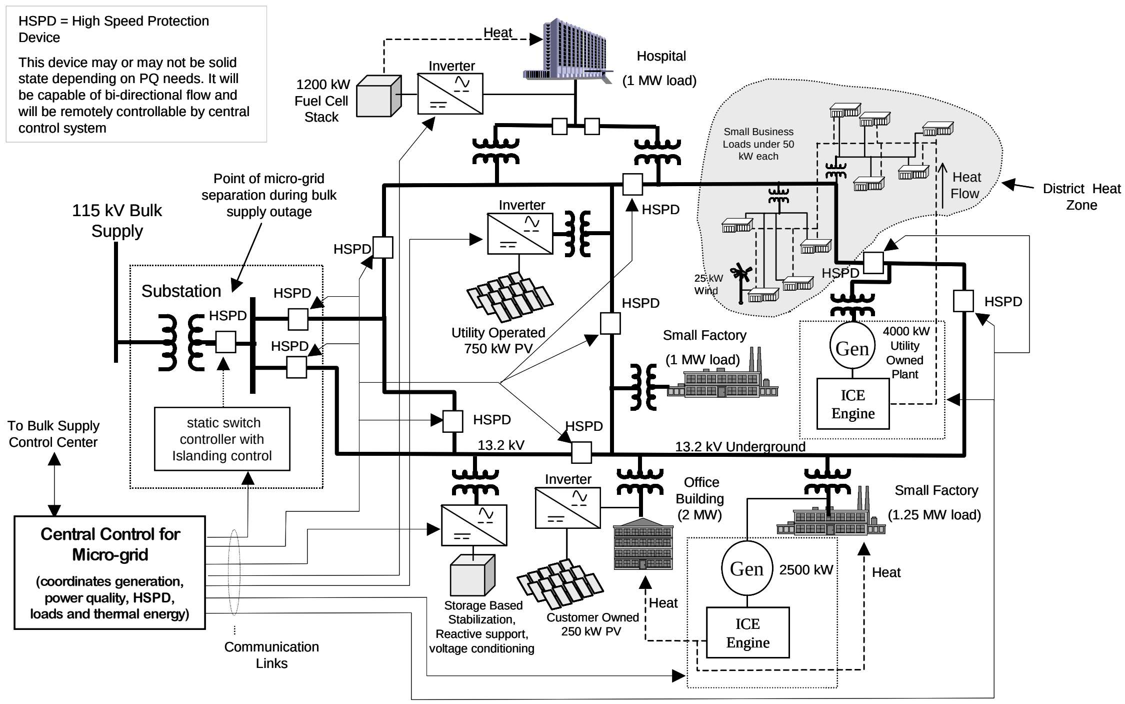

Figure 2-10
Networked Primary-Based Micro-Grid Adapted for Power Quality Business Park Application

Low-Voltage Grid Network Micro-Grid Example

Low-voltage network architectures operating at 208 or 480 volts, such as those found in large cities, may be adapted to micro-grid applications. A conventional low-voltage network is not suitable for micro-grid operation because the network protectors and operational practices do not facilitate safe or reliable operation of distributed generation. However, the basic architecture of a low-voltage network can lend itself quite effectively to a micro-grid mode of operation if two conditions are met:

1. Network protectors are replaced with “self-synchronizing interrupting devices” that are rated to serve as a separation device between two systems

2. The proper protection and control is utilized on all of the generation systems connected at the low-voltage grid level

Figure 2-11 is an example of a very advanced low-voltage grid network that can operate as a unified micro-grid (meaning that all low-voltage cells are connected and synchronized), or the network can operate broken apart into various independent cells. The high-speed, low-voltage sectionalizing devices shown on the low-voltage grid can be used to isolate faulted sections and/or configure the grid into various states of consolidation. Networked microprocessor-based controllers are integrated into each generator and switching device and allow all key elements to communicate back to the master controller such that load sharing and frequency/voltage control can be established. Operating much as a packet-data-switching network, the units allow high-speed propagation of data around the grid network via redundant paths. The communication paths in the figure represent just some of the possible options. The communication medium might be power-line carrier, fiber-optic, hardwired, Internet, or radio. Speed and security issues for the communication/control would be a concern.

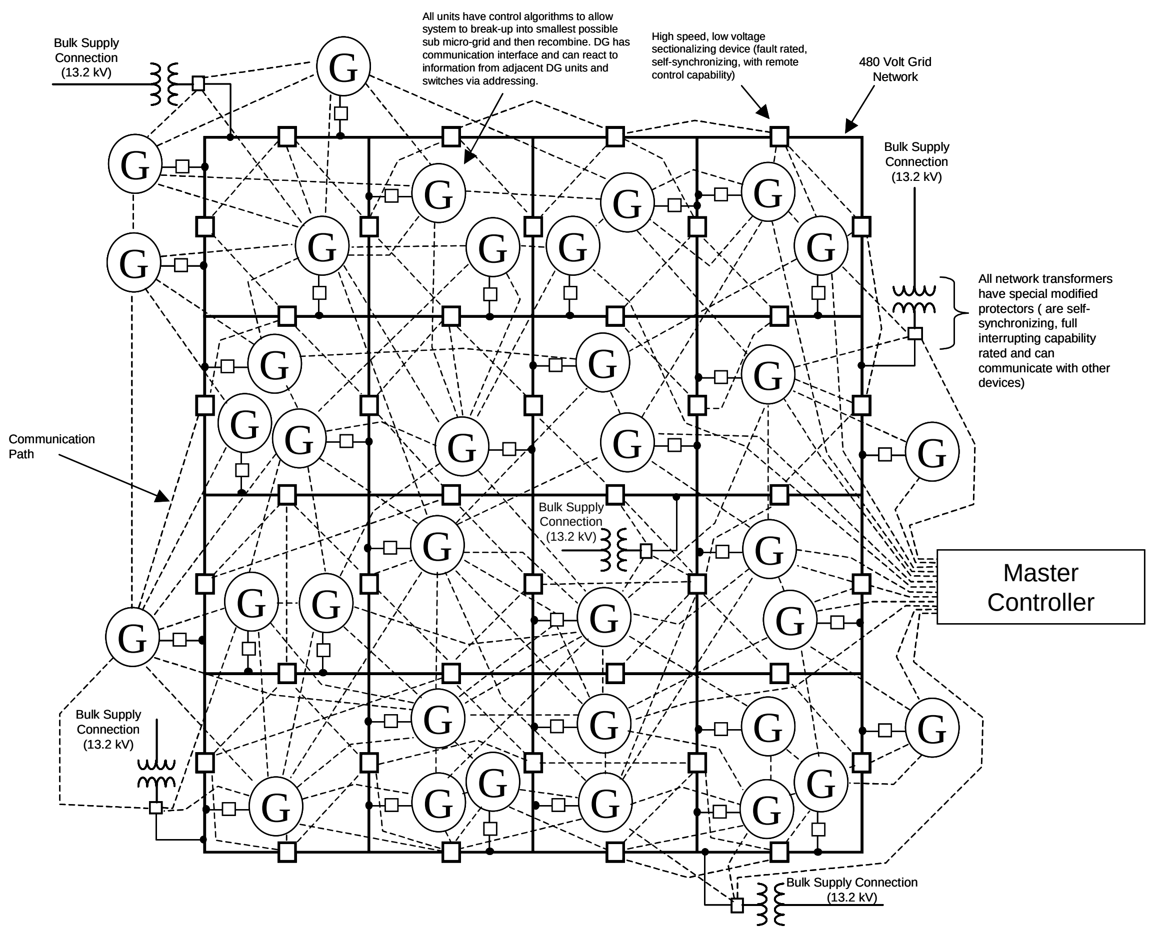

Figure 2-11
Low-Voltage Network Micro-Grid with Networked Communication Paths between Generators, Switching Devices, and Master Controller

Voltage Levels of Micro-Grids

Just like a conventional power system, the suitable voltage level for a micro-grid depends on several factors, including the system layout (network, looped, or radial), load density, physical distance between loads and generators, and various other operating issues. Small micro-grids can be developed that operate at any of the standard utilization voltages, including 120/240, 208Y, or 480Y. For much larger micro-grids, any of the 5, 15, 25, or 35-kV class distribution voltages are possibilities. For example, in the 15-kV class, voltages of 12.47, 13.2, or 13.8 kV are commonly employed in standard distribution systems and would also make sense for a variety of micro-grid designs. It is advantageous to use standard voltage levels so that existing commercially available equipment can be utilized as much as possible. There may be some non-standard voltage levels that could be used such as in the case of a DC micro-grid because those systems would employ non-standard equipment anyway.

For micro-grids of radial design that employ a single generation site (like those of Figures 2-3 through 2-6), the engineering design practice for selecting suitable voltage levels is quite similar to that for conventional radial distribution systems in that a single-source injection point is employed and the designer must consider conductor thermal and voltage drop limits to handle the loading conditions at all points on the feeders. Loading will be high near the source and will drop off with distance from the source feed point. The designer must aim to keep all voltages delivered to customers within required limits (+/- 5% of nominal) and make sure that conductor ampacity is not exceeded at any point.

Use of low voltage (< 600 V) on radial micro-grids employing a single-generation site would generally only be suitable for applications where the generators are no more than a few hundred meters from the loads and where the loads are fairly light (less than 1 MVA of total load). Otherwise, the voltage drop would be too great. For loads greater than 1 MVA and where distances are greater than a few hundred meters, a primary distribution system between 4.8 and 34.5 kV would more likely be used to achieve suitable voltage regulation and reduce the need for larger conductors. Table 2-1 provides some guidance on typical capacities and areas that can be served per circuit using radial system designs with single-point generation sources.

Table 2-1
Area Served and Maximum Load For Typical Distribution System Nominal Voltages

Nominal System Voltage	Typical Maximum Loading Limits per Distribution Circuit with Commonly Used Conductors	Approximate Typical Area That Can Be Served per Circuit (km^2) *
480 V	0.1-0.5 MVA	< 0.1
4.8 kV	3-5 MVA	1-10
13.2 kV	7-13 MVA	5-30
25 kV	13-25 MVA	10-60
34.5 kV	18-35 MVA	15-90

*Service areas are illustrative of those found with load densities ranging from typical rural to typical suburban. Areas served will be less in high-density urban environments.

Voltage Levels for Micro-Grids with Multiple Dispersed Generation Sources

For micro-grids with multiple dispersed generation sources, the voltage drop and loading are an entirely different situation, and the conventional design approaches no longer apply. Here, it is likely that generators will be sited right at or very close to loads, which significantly reduces the loading on any section of the line. For this type of arrangement, the onsite generation is adjusted to nearly match the load, and the interconnecting lines are mainly in place to facilitate reliability in case of loss of local generation at any one site and to assist local generation in handling transient load steps. The wires are not intended for significant transfer of power over significant distances. With this type of configuration, the reduced wire loading can make it possible to use a much lower distribution voltage compared with the design of a conventional distribution system that is fed from one end. To understand this, consider Figure 2-12. It is a hypothetical example comparing a single-end-fed source (see “Single Generator Case” in the figure) to seven smaller dispersed sources each located at the load (see “Smaller Dispersed Generator Case” in the figure). With the single-end-fed source, the triplex conductor simply has too much impedance to allow sufficient voltage at the end when using only 240-volt power distribution, so it cannot be successfully used for that type of arrangement. However, with the dispersed generators, the triplex does provide sufficient voltage because current flows are relatively small or non-existent between houses. Also, note that the design contingency for the loss of any single dispersed generator has been accounted for in that the adjacent generators can pick up the load of an adjacent house and the voltage drop will still be within limits.

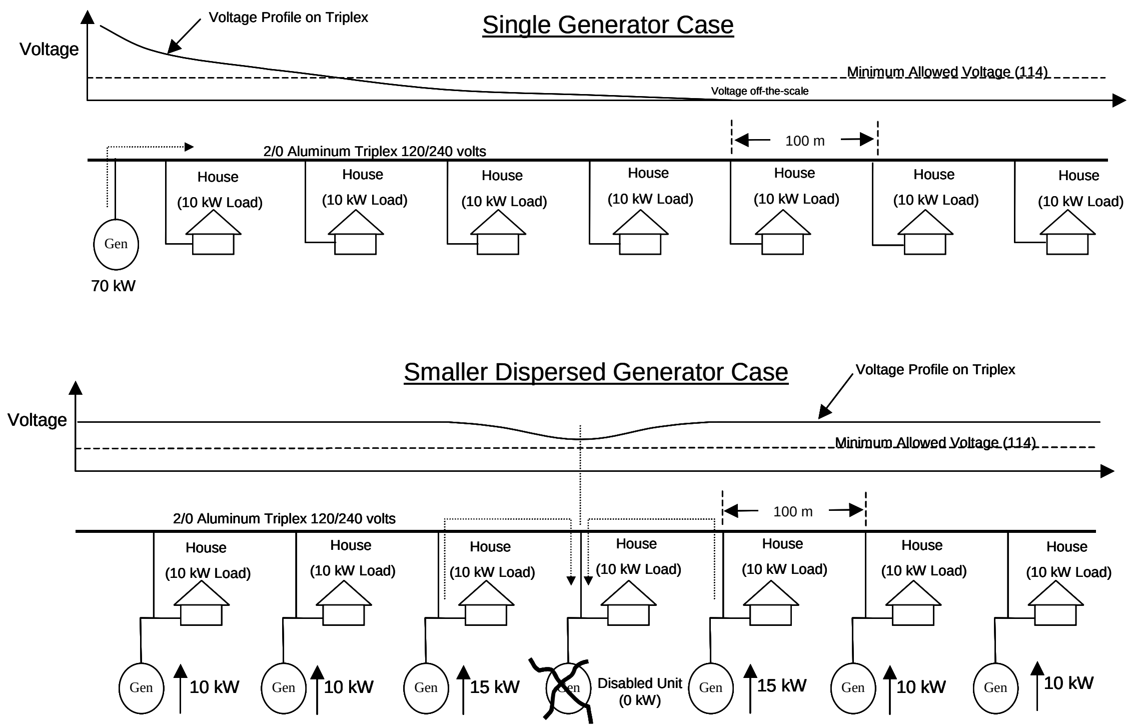

Figure 2-12
Example Showing Voltage Drop Limitations When Attempting to Feed a Circuit with a Single Source from One Side

The example in the figure was based on a radial micro-grid with uniformly dispersed generation, but a network grid would benefit even more greatly from these characteristics because it would offer parallel paths to all loads that help to further reduce voltage drop and help stiffen up the system. A networked low-voltage micro-grid could conceivably cover an enormous area, assuming it was well designed.

The ability to successfully operate a power system with a voltage less than the nominal voltage of a traditional distribution system, as is shown in Figure 2-12, depends on the uniformity of the load distribution and generator distribution on the system. If loads and generators are uniformly dispersed and are relatively equal in size at each site, then little power transfer is needed between loads and voltage drop would not be much of an issue. However, existence of large load pockets or generation pockets that are location-mismatched would increase the power-transfer capacity needed on the wires and would likely force a more traditional selection of voltage level and wire capacities.

By avoiding the use of high-voltage distribution, there can be considerable cost savings in equipment, operation, and maintenance. Also, there are certain safety advantages. In equipment and wires, insulation costs would be reduced, but the size (cross sectional area) of conductors *might* be increased. Therefore, metallic cost increases must be weighed against insulation cost savings. Mechanical switchgear can be much less expensive at the low-voltage level. Because many systems would employ power electronic switching devices, this would be particularly important because such devices are very costly if they must operate at high voltages. Crews working on systems could apply low-voltage safety practices instead of high-voltage practices, and the public would generally experience less risk due to fallen conductors and so on.

There are some power quality/reliability benefits, too. First of all, flashovers due to lightning and other events would in many cases be self-healing, without the need for operation of an interrupting device. This should help reduce the duration and depths of voltage sags and reduce the incidence of interruptions. Second, the use of a lower-voltage design with higher impedance when coupled with dispersed generation should reduce the propagation distance of major fault-related voltage sags.

In thinking about this low-voltage architecture, it is very intriguing to consider the future possibility that the use of *highly dispersed generation* at the distribution level could allow low voltage to be used extensively and eliminate the need for most transmission and high-voltage distribution in all but the more demanding load situations. In the future, much of U.S power system may become a cluster of interconnected low-voltage micro-grids. This cluster will be able to break apart into numerous sub-grids in the event of a problem with any particular section. With the need for power transfer reduced, one can see many small towns and cities in the future operating almost entirely at less than 600 volts. Of course, in the near term, many micro-grids will not have this type of layout and will employ more traditional operating voltage levels familiar to most radial distribution systems.

Networked versus Radial Micro-Grid

As has been shown in various examples, a micro-grid can be created out of either a networked or radial architecture, so there is not a technical impediment to either approach. However, the question is, “Which approach is most suitable for micro-grid operation?” The choice of a networked versus a radial system will be based on the environment in which the micro-grid is located, the economics of applying these architectures, and the expected needs of power users. Some possible design options include:

- Radial system with high-voltage distribution
- Radial system with low-voltage distribution
- Low-voltage networked system
- High-voltage networked system

In traditional power system designs, low-voltage network architectures make sense only in areas with high load density, such as large cities. Rarely would low-voltage networks be used in small towns or villages, and never in rural areas. However, the rules that apply to traditional power systems do not necessarily apply to micro-grid situations because the capacity of the wires relative to total system load can be much lower for some micro-grid designs. There are many rural and small town environments that can be ideally suited to a micro-grid-based low-voltage network architecture. For example, a rural housing development of 20 homes may be quite remote from a major city. However, within the housing development itself, the homes could be within a few hundred meters of each other, and a low-voltage network consisting of meshed interconnected secondary connections can make sense for those houses. Network architecture has the advantage that the redundant paths could be helpful in stiffening up the voltage regulation on the micro-grid and also enhance its reliability, albeit at some extra cost.

Probably the key factors that determine when a network architecture makes sense is the distance between loads and whether or not low-voltage distribution can be used. In deep rural environments, loads are separated by up to a kilometer or more. In such cases, high-voltage distribution must be used because low-voltage distribution would be technically impractical at such distances due to voltage drop and losses. A high-voltage network could be achieved, but would be costly due to the redundant circuit paths and numerous high voltage protection devices that would be required. Consequently, in very rural situations, either single-customer micro-grids or radial-connected micro-grids with high-voltage distribution and step-down transformers to utilization levels would make the most sense.

In suburban environments or rural towns/housing developments where clusters of loads are located within a few hundred meters of each other, a low-voltage networked micro-grid or an entirely low-voltage radial micro-grid can make sense. However, there are a number of factors that must be considered. First, the nature of the dispersed generators on the system will impact the wire sizes that are needed and configurations that can be used. As stated in the earlier discussion on voltage levels, the more dispersed the generation, the less capacity the distribution system wires will need. Figure 2-13 shows some different system configurations that make this point. Systems with fewer sources generally will require larger power-transfer capacities on the wires. Therefore, Figure 2-13A requires a more robust distribution system than the situation of Figure 2-13B. The same is true in comparing Figure 2-13C to Figure 2-13D. Systems that have only a few larger sources will likely need to be high-voltage systems and most likely high-voltage radial micro-grids. On the other hand, those with many dispersed sources may be entirely based on low voltage and therefore are more suitable for either a low-voltage radial or low-voltage networked architecture.

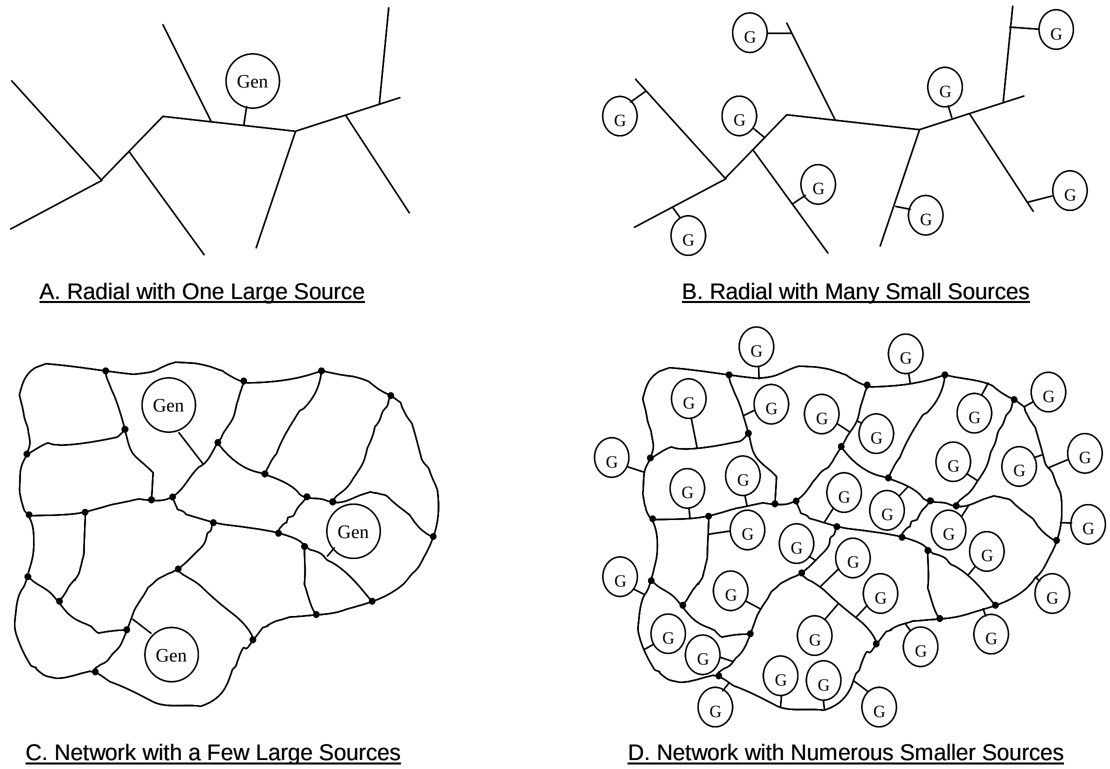

Figure 2-13
Micro-grids May Be Networked or Radial, Depending on the Environments in Which They Are Applied (Connections to Bulk Supply Not Shown)

The cost of a networked low-voltage micro-grid (Figure 2-13D) will probably not be much higher than a radial low-voltage micro-grid (Figure 2-13B). This is because the protection and control of both types of micro-grids can be similar from an equipment-cost perspective. The main extra cost of the networking approach is a matter of the extra trenching and wiring needed to create the meshed low-voltage connections. The main factor in determining this added cost is the layout of the roads and houses in the neighborhood. Some road layouts are best suited for radial distribution systems, and grid layout of roads are suitable for a networked secondary design.

AC versus DC Micro-Grids

Early power systems of the Edison era were often direct current (DC) micro-grids. Today, there is much interest in the possibility of revisiting DC as a means for distributing power on such systems. Reasons why DC may make sense include:

- Many distributed generation sources such as photovoltaic cells and fuel cells already generate their energy as DC power. Other generation devices can also be better suited to DC output, including micro-turbines, wind turbines, and storage devices (batteries, flywheels, and capacitors).

- Use of DC power avoids synchronization issues and reduces stability concerns that occur with conventional AC generators
- During the steady-state operation, the use of DC power avoids the reactive voltage drop that occurs with AC power thus extending the voltage reach of distribution systems
- Many loads can operate satisfactorily from DC power, so the power is already in a form that avoids unnecessary conversion
- Improved inverters and power electronics allow DC power to be converted easily and efficiently to different voltage levels and to AC power
- A line of a given voltage rating can transmit much more DC power than AC power

Of course there are also significant drawbacks to DC power. First and foremost, transformation of DC voltage levels from primary levels (several thousand volts) down to utilization levels in homes is much more costly and somewhat less efficient than present-day distribution transformer technologies using AC. Fault protection of high-voltage DC distribution systems is problematic and more costly due to the lack of a zero crossing point and limited availability of protection equipment designed for DC. Finally, even though many electronic devices (PCs, TVs, etc.) ultimately operate on DC, these devices are still expecting AC and have been designed for such current – so for some time to come, 60-Hz power still needs to be supplied to loads.

Despite these drawbacks, the list of advantages for DC is very intriguing and it makes sense to consider it as a possible option for future micro-grid designs. One of the most interesting potential applications may be for low voltage DC micro-grids (either of radial or networked design). This approach avoids the high cost of developing a "DC transformer" that can convert primary voltage down to utilization levels. Furthermore, for DC systems, the lack of reactive voltage drop helps make it possible to increase the reach of a low voltage system perhaps 50-100% further than an AC system with similar size wires. DC also makes it easy to avoid back-feeding surplus generation and fault contributions into the bulk utility system (by the use of a rectifier that only allows one way power flow). This reduces the complexity of interconnection of the micro-grid to the bulk power system.

Figure 2-14 shows an example of a small DC micro-grid serving about 10 homes. The example employs a combination of solar, wind, fuel cell, and energy storage, all feeding a 400-volt DC distribution system. Inverters at each house provide conversion of DC to 60 Hz AC power. DC-level converters (DC to DC converters) are employed at all sources to match generator output voltage to the distribution voltage. The 60-Hz bulk power system is connected via a rectifier/regulator package that prevents backfeed into the utility system during faults and periods of excess generation. During power quality disturbances on the utility system, the voltage on the DC distribution system does not collapse due to energy storage and the blocking effect of the rectifier.

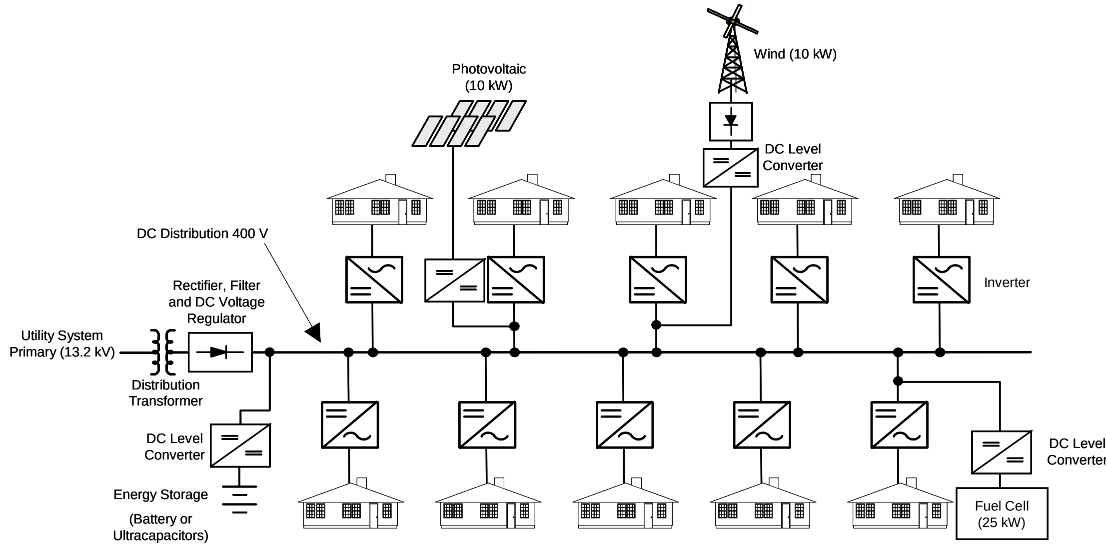

Figure 2-14
A Simple DC Micro-Grid Employing Renewable and Fuel Cell Sources

One of the advantages of DC is the ability to use *blocking diodes* at key points within the micro-grid to isolate faulted sections and limit exposure to voltage sags. Figure 2-15 shows an 800-volt DC radial type micro-grid that employs numerous blocking diodes. When faults occur upstream of the blocking diodes, downstream generators are not able to feed into the faults. A small amount of storage can be employed along with each diode-protected section to ensure that upstream faults do not cause voltage sags on other regions of the micro-grid (this assumes the generators have sufficient capacity to carry the section). Blocking diodes may also be used with network architectures to provide the same isolating function, but more would be needed. Blocking diodes can be reversed by a mechanical switch to allow a change in power flow direction. An even more advanced solution is to use high-speed SCR devices (similar to AC static switches but operated with DC) that could be employed to allow instantaneous directional flow change when needed to reconfigure the DC micro-grid to support a new flow direction in the event of a loss of utility bulk supply or other problems. Another use of blocking diodes and SCR devices is the ability to simplify generator “zone” protection requirements on complex systems. Fault currents can be “steered” and controlled in a manner that helps identify which zone the fault is actually located in, so setting up the generator protection and control becomes much easier.

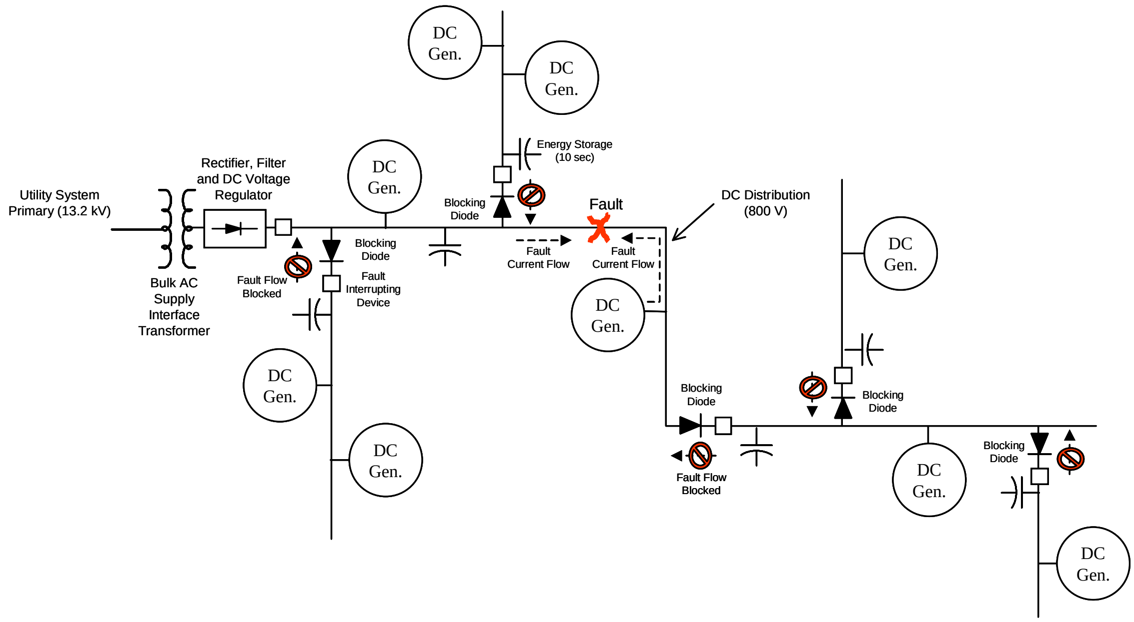

Figure 2-15
Extensive Use of Blocking Diodes Can Allow Improved PQ for Unfaulted Sections and Control of Fault Contributions from Generation Devices

Overall, DC micro-grids appear to have many advantages over their AC counterparts once the key technical elements evolve a bit further in capability and cost. Right now, the technical status of inverters and other elements needed for DC means that they are not ready for commercial wide-scale adoption. However, now is a good time for pilot projects to demonstrate such systems. Further evolution in fuel cells and other DC sources is also needed to facilitate their development.

Power Generation Equipment for Micro-Grids

The generation technologies that may be used for typical micro-grid systems include:

- Internal combustion engines (10 kW to 10 MW)
- Mini to small-size combustion turbines (0.5 to 50 MW)
- Microturbines (20 to 500 kW)
- Fuel cells (1 kW-10 MW)
- Photovoltaic systems (5 W to 5 MW)
- Wind turbines (30 W to 10 MW)

The size ranges shown adjacent to each technology are suggested as the most likely implementation of the above technologies given the current status of these generation technologies. However, application of units larger or smaller than indicated is also possible. Examples of these technologies are shown in Figure 2-16.

Photovoltaic Microturbine Wind Internal Combustion Engines

Figure 2-16
Example of Photovoltaic, Microturbine, Wind, and Internal Combustion Engine Energy Resources

Because micro-grid generation is located at or near loads, it must be suitable for use in load environments and must be placed where it can operate without causing problems with noise, emissions, aesthetics, and other site-related issues. Ideal micro-grid generation technologies will have the following characteristics:

- Modular design (scalable from 1 kW up to 10 MW)
- Low capital cost (preferably much less than $1000/kW installed)
- Low operation and maintenance cost
- Suitable for residential, commercial, and industrial permitting constraints
- Low emissions (meet or exceed those of large modern gas-fired power plants)
- High efficiency over broad range of loading conditions (at least 40%)
- Usable waste heat (higher exhaust temperature is usually better)
- High power quality (low harmonics, good voltage and frequency regulation)
- Good load-following characteristics (for large load steps and transient motor starts)
- Rapid start up (from cold start and standby conditions)
- Good energy density (high power/weight and high power relative to footprint area required)
- High reliability and dispatchability
- Resistant to damage by power system voltage and current anomalies (surges, voltage unbalances, and so on)
- Operate on fuel that can be easily delivered or transported to the site
- A mature technology with excellent support infrastructure

None of the available distributed generation technologies meet all of the ideal characteristics above. For example, fuel cells get high marks for emissions, modularity, and their ability to be integrated into residential/commercial sites with minimal siting concerns. However, they currently suffer from high capital cost and still are considered an early commercial and/or developing technology that needs further technical improvement. On the other hand, internal combustion engines are very mature, have excellent support infrastructure, and have low capital cost, but they are not ideal for some applications due to noise and emissions issues. Table 2-2 is a matrix of the various distributed generation technologies showing the advantages and disadvantages of each as related to siting and cost.

Table 2-2
Distributed Generation Technologies For Micro-Grids (Data Are for Year 2001)

Generation Technology	Capital Cost Range ($/kW)	Cost of Power (cents/kW)	Typical Application Size	Site Footprint (area/kW)	Reliability	Primary Siting Issues	Most Likely Near-Term Micro-Grid Applications
Internal Combustion Engine (ICE)	300-900	7-15	All DG sizes	Good	Very good	Noise, fuel supply, and emissions	Various Commercial/industrial /utility scale applications
Conventional Combustion Turbine (CT)	500-1000	5-15	> 1MW	Excellent	Excellent	Noise, fuel supply and emission	Larger Commercial/industrial/utility scale applications
Micro-turbine	700-1000	9-15	< 500 kW	Good	Still maturing but can potentially be excellent	Noise, fuel supply and Emissions	Smaller Commercial/industrial/utility applications
Photovoltaic	5000-8000	20-40	All sizes possible (less than 10 kW most common)	Poor	Intermittent resource: not reliable without storage	May be problematic visually, resource availability, no noise issues	For micro-grid support only unless storage is used
Wind Turbine	700-1200	4-20	Better economics for > 1 MW sizes	Poor	Intermittent resource: not reliable without storage	Very problematic visually, resource availability, and potential blade noise issues	For micro-grid support only unless storage is used
Fuel Cell	4000-50000	15 or more	Most DG sizes being developed (4 kW up to 3 MW)	Good	Still maturing but can potentially be excellent	Fuel supply	Residential, commercial and industrial

Generation sources that are suitable for a micro-grid need to be selected based upon cost, siting restrictions, fuel availability, and other technical factors as described in Table 2-2. Technologies that have the lowest energy cost (such as ICE) may not be usable in some locations due to emissions issues, noise, zoning, fuel infrastructure, and so on. More costly technologies such as fuel cells and renewables may be a better option when emissions restrictions or fuel issues constrain the use of the lower-cost traditional generation options.

In addition to the cost and siting issues related to the DG technologies, there are also electrical performance issues that impact the ability of a particular technology to be used successfully for a micro-grid. Probably the most important factors are the reliability/availability of the source, its ability to load follow, and its efficiency at loading levels that are less than rated power. The ICE is one of the best all around technologies for performing both base-load continuous operation as well as for load following and handling transient load steps. So micro-grids composed of considerable ICE capacity should perform very well handling day-to-day fluctuations in loading and typical load steps. Technologies such as wind turbine and photovoltaic energy sources are intermittent renewable energy sources that are not considered dispatchable. They cannot be counted on as the primary source for the micro-grid (unless considerable electrical energy storage is utilized). These intermittent renewables, without storage, probably cannot constitute more than about 20% of the generation capacity on the micro-grid. Otherwise, frequency and voltage control issues may arise and the grid may need to shed load to keep operating.

Other generation devices such as fuel cells and micro-turbines should in theory perform well at load following because they employ inverters. However, not all present-day fuel cell and microturbine control systems have been designed to handle large load steps, so some perform well while others do not. Micro-turbines in particular are not very efficient at light loading, and therefore it makes more sense to operate them near their rated power instead of using them for load following. This is probably why some manufacturers have focused on this mode of operation for those devices. If a micro-grid is being designed, the planner needs to consider the load fluctuations that occur on the grid and employ a suitable portfolio of generation technologies. Many early micro-grids will be based on ICE units, and these micro-grids should operate well for most conditions unless very large load steps and motor starts occur. Future micro-grids may include a large amount of wind and solar capacity that may need to be stabilized with some energy storage to assist in the operation of the system. A good mix of base load, load following, and intermittent renewable resources coupled with energy storage can be operated successfully as a micro-grid with just about any load characteristic.

The reliability of generation sources will also play a key role in the implementation of the micro-grid. The best available ICE and CT technologies have availabilities of 0.90 to 0.98, whereas the availability of a typical conventional utility system is usually better than 0.999. Thus, redundant generator sources are necessary to ensure that respectable levels of reliability are achieved for a micro-grid that meet or exceed the levels that customers have become accustomed to on conventional T&D systems. This requires the use of excess generation capacity in the design of the system. The amount of excess depends on the number of generators employed and system load characteristics. This analysis is discussed in detail later in this report.

Table 2-3 summarizes some of the electrical compatibility issues associated with various DG sources. These performance characteristics in part determine if a source is good for base load or load following type of applications.

Table 2-3
Micro-grid Electrical Compatibility Characteristics of DG Sources

Generation Technology Type	Most Common Power Converter Employed	Load Following Capability	Relative Efficiency at Less Than Peak Load	Fault Current (per unit of Rated Current)	Reliability/Availability	Best Current Usage in Micro-Grid Application
Internal Combustion Engine (ICE)	Synchronous Generator	Very good	Fairly good down to 35-40% of rating	Initially 5-10X	90-96% depending on maintenance	Well suited to both based load and load following on micro-grids. Perhaps the best all around source presently available (electrically speaking)
Conventional Combustion Turbine (CT)	Synchronous Generator	Fair/Good	Fair down to 40% of rating	Initially 5-10X	90-98% depending on maintenance	Not as good as ICE at load following, better suited to base loading – still can load follow somewhat if necessary
Micro-turbine	Inverter	Potentially good (but current designs only fair /poor)	Declines faster than others below 40%	Depends on Inverter Design (<4X)	?	Poor efficiency at light loads means it is better suited to full continuous operation (base load). Current versions don't load follow well but future versions may load follow better.
Photovoltaic	Inverter	None (unless storage is used)	NA	Depends on Inverter Design (<4X)	8-25% (based on resource at site)	Only suitable for use as an intermittent peak shaving source that does not exceed the ability of other micro-grid sources to compensate for its fluctuation– probably limited to less than 20% of micro-grid generation capacity unless storage is utilized
Wind Turbine	Inverter or Induction Generator	None (unless storage is used)	NA	5-10X for induction designs Inverters less than 4X	10-40% (based on resource at site)	Only suitable for use an intermittent peak shaving source that does not exceed the ability of other micro-grid sources to compensate for its fluctuation – probably limited to less than 20% of micro-grid generation capacity unless storage is utilized
Fuel Cell	Inverter	Fair to good depending on design	Fair/good down to about 35-40%	Depends on inverter design (<4X)	90-95% and getting better as units improve	Can be an excellent resource for both load following and base-load operation – some products load follow better than others depending on inverter design

In selecting generation sources for micro-grids, it is very important to recognize that Table 2-2 and Table 2-3 represent the current status of these technologies. All of the DG technologies, including the mature technologies such as ICE and CT, are improving in performance and cost with time. For ICE units, much work is underway to lengthen maintenance intervals, improve efficiency, lower emissions, and reduce cost. The same is true for combustion turbine products. As a result, these traditional devices will become more competitive with conventional power systems over the next 5 to 10 years. The emerging technologies such as microturbines, fuel cells, and renewable energy sources are currently more costly than the conventional technologies such as ICE and CT, but they probably have more potential room for improvement in cost and performance due to their being at a less mature point on the development curve. In 5 to 10 years, these new emerging technologies *may* surpass the others in performance and become the preferred micro-grid technology.

Reliability of Micro-Grid Generation

The reliability of the micro-grid in terms of its ability to serve the load will depend on its physical configuration, power transfer capacity, the characteristics of generators, and loads on the system. In general, the larger the number of generators employed on the system, the less surplus generation capacity needed to survive the contingency of the loss of any single unit. Figure 2-17 shows this concept. Note that with two generators (option B), each one must be sized large enough to carry the load during the loss of any single generator. This results in the need for generation capacity that is double the size of the load. For seven generators, such as in option D in Figure 2-17, only about 16.7% overcapacity is needed to handle the loss of any single generator.

One complication is that as the number of generators increases, the probability of any one unit failing also increases. In addition, the load may not be constant but rather have a daily cycle. Therefore, there is a certain statistical probability that a generator will fail during an off-peak period when load is light. This would enable less needed overcapacity to ride through that situation, so one might design a system that can ride through a failure most of the time but not all of the time. Another complicating factor is that generators have short-term overload capacity, which can be used to ride through situations where adjacent units are down for short periods. When intermittent renewable resources are thrown into the mix of generation, this further complicates the issue because predicting their output is difficult. Overall, the issue of sizing for reliability is complex and requires a thorough analysis of many factors. The next section discusses in more detail some of the methods that can be used to determine the ideal number of generators and overcapacity needed to carry a load with a given level of reliability.

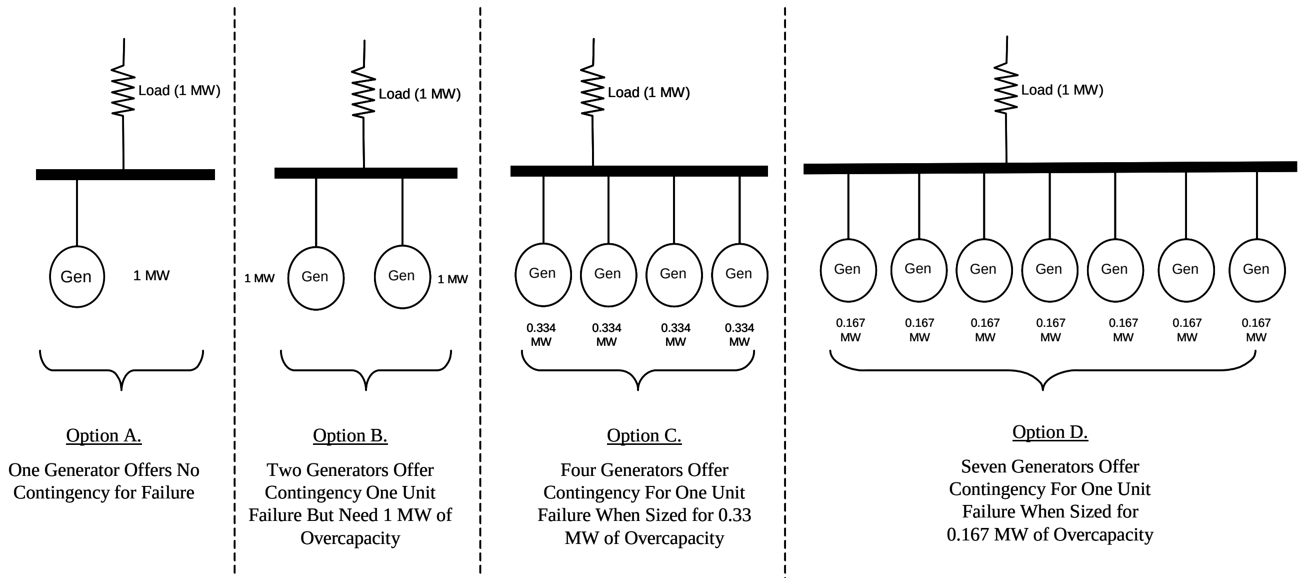

Figure 2-17
The Needed Overcapacity of Generation for the Micro-Grid to Ride Through the Contingency of the Loss of a Single Unit Decreases as the Number of Generators Increases

Probability Analysis for Reliability of Micro-Grid Generation

To determine the adequacy of a micro-grid to achieve a given level of reliability performance, we must characterize the dependence of several key variables and evaluate how each or a combination of these affect the overall performance of such a system. The variables include:

- Level of system reliability (example, if a system has a loss of load probability (LOLP) of 2 days in 10 years, then the system reliability is 99.9452%)
- Type of generating units (PVs, non-co-generative fuel cells, co-generative fuel cells, or hybrid units comprising PV arrays and co-generative fuel cells)
- Number and size of the generating units
- Number and types of customers (residential, commercial, or a combination of both)

Given the above parameters, the first step involves estimating the load demand (hourly, weekly, monthly, annually, and so on) of a stand-alone system as a function of the number and type of customers. Figure 2-18 illustrates this sample variation during a particular point in time.

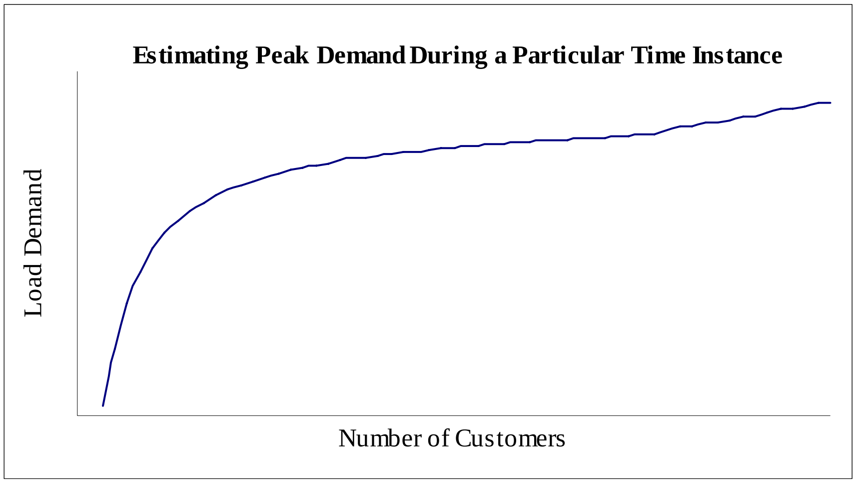

Figure 2-18
Demand Versus the Number of Customers

The next step requires a LOLP to quantify the number of generating units that must be installed to obtain a given level of reliability as a function of the size of each unit and the number of generating units (the total firm capacity). Figure 2-19 illustrates a sample of what results might look like for a given size of generation. This process will then be repeated for different unit sizes.

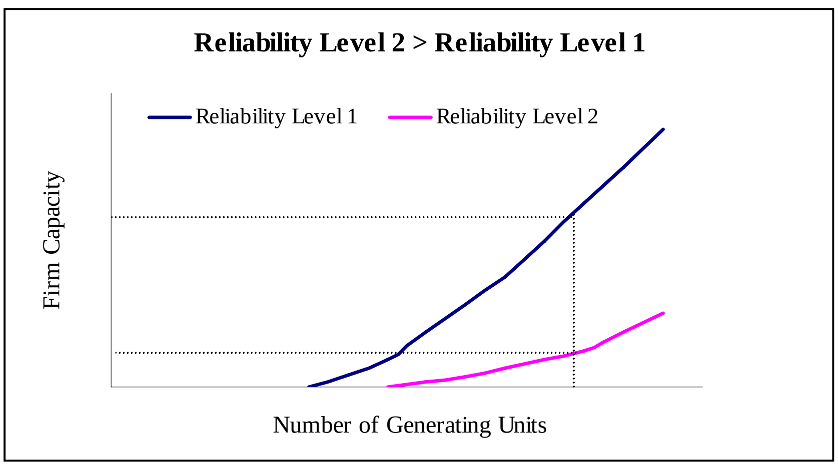

Figure 2-19
Variation of Firm Capacity versus Number of Generating Units

The third step then would be to combine the results of Figure 2-18 and Figure 2-19 (for all levels of demand throughout a time period, for example hourly, weekly, monthly, and annually) to evaluate the adequacy of a system for a range of customers, number, and size of generating units (PVs, fuel cells, or a hybrid system). Figure 2-20 illustrates a sample of what the results might look like for a given size of generation. This process will then have to be repeated for different unit sizes. As the figure suggests, a system with more generator units will be more reliable.

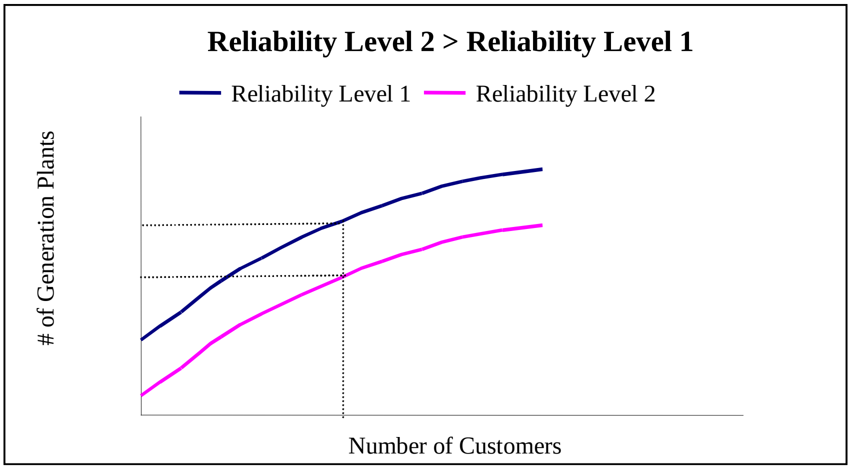

Figure 2-20
Variation in the Number of Customers versus Number of Generating Units

As can be seen from the preceding discussion, finding an optimal micro-grid configuration can be very complex due to the number of variables involved. A simplified approach [1] is illustrated in the following example with a 100-kW constant-load micro-grid. First, it is assumed that the local load demand is held constant at 100 kW (hourly, weekly, and annual load variations are not considered). Forced outage rate for each generation plant is 5%, and the desired level of system reliability is 99.97% (1 day in 10 years the demand will exceed supply). The distributed resources used are dispatchable conventional plants and not intermittent renewable resources, so our example does not need to consider those variations (which would seriously complicate the analysis).

Figure 2-21 presents the results of a detailed cumulative probability distribution analysis for six possible system configurations that could be used to support the 100-kW constant-load micro-grid. These are:

- System with 5 plants (each unit is 20 kW)
- System with 10 plants (each unit is 10 kW)
- System with 20 plants (each unit is 5 kW)
- System with 25 plants (each unit is 4 kW)
- System with 50 plants (each unit is 2 kW)
- System with 100 plants (each unit is 1 kW)

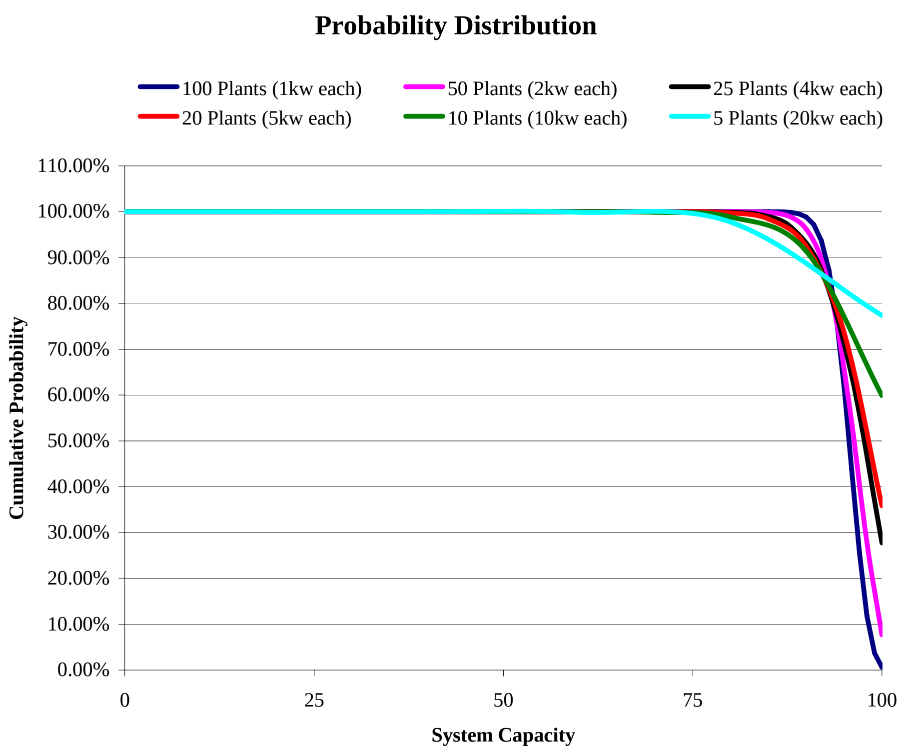

Figure 2-21
Detailed Probability Distribution That the System Capacity Will Be Greater Than or Equal To a Certain Value (For the 6 Different System Configurations)

Table 2-4 provides steps to perform a detailed probability analysis using a system that consists of 10 plants (each unit is 10 kW).

Table 2-4
A Sample Cumulative Probability Calculation (10 Plants with 10-kW Units – Forced Outage Rate Is 5%, Reliability Is 99.97%, and Total Capacity Is 100 kW)

Combinations	**# of Units** on Outage	**Probability**	**X kW** or More in Service	**Probability of X kW** or More in Service
1	0	0.599	0	100.000%
11	1	0.315	10	100.000%
56	2	7.463E-2	20	100.000%
176	3	1.048E-2	30	100.000%
386	4	9.648E-4	40	99.9999%

638	5	6.094E-05	50	99.9997%
848	6	2.673E-06	60	99.9936%
968	7	8.038E-08	70	99.8971%
1013	8	1.586E-09	80	98.8496%
1023	9	1.855E-11	90	91.3861%
1024	10	9.766E-14	100	59.8736%

Table 2-5 provides estimates of the firm capacity for the six different system configurations. These results were then verified using the empirical formula shown in (2-1). Equation (2-1) was first proposed in [1] and was developed using about 350 points that were generated using the similar probability distribution illustrated in Table 2-4 and Figure 2-21. The inputs required for formula development included different plant sizes (N), reliability levels (D), and forced outage rates (FOR). The output R is the ratio between system capacity and demand.

$$\begin{aligned} &R = \exp\left\{A\left[\ln(N)\right]^{B}\right\} \\ &\textit{where} \\ &A = 1.2 - 0.212\ln(D) + \left[14.4 - 2.139\ln(D)\right](FOR) \\ &B = -1.159 + 0.1024\ln(D) + \left[0.1689 - 0.00512\ln(D)\right]\ln(FOR) \end{aligned} \tag{2-1}$$

Table 2-5
Firm Capacity Values for Different System Configurations (Reliability Level Is 99.97%)

	Firm Capacity Evaluation	
Different System Configurations	**Detailed Binomial Distribution**	**Empirical Formula**
5 plants (each unit is 20 kW)	40 kW	41.9 2kW
10 plants (each unit is 10 kW)	60 kW	61.95 kW
20 plants (each unit is 5 kW)	75 kW	73.42 kW
25 plants (each unit is 4 kW)	76 kW	76.02 kW
50 plants (each unit is 2 kW)	82 kW	82.03 kW
100 plants (each unit is 1 kW)	86 kW	85.98 kW

It is clear from the results obtained from Figure 2-21 and Table 2-5 that for a given level of system capacity (assumed here as 100 kW), the system composed of a larger number of smaller plants provides more firm capacity at the desired reliability level than a system with a fewer number of larger units. Capacity of individual plants sizes (six different system configuration) required to meet a firm capacity level of 100 kW is provided in Table 2-6.

Table 2-6
Calculation of Individual Plant Sizes Required to Maintain a Firm Capacity of 100 kW

Different System Configurations to Maintain a Firm Capacity = 100 kW
Individual Size for 5 plants = (20*100/40) = 50.0 kW
Individual Size for 10 plants = (10*100/60) = 16.7 kW
Individual Size for 20 plants = (5*100/75) = 6.7 kW
Individual Size for 25 plants = (4*100/76) = 5.3 kW
Individual Size for 50 plants = (2*100/82) = 2.4 kW
Individual Size for 100 plants = (1*100/86) = 1.2 kW

Reliability Evaluation for Variable Loads

Even though the results in the previous section serve as an excellent tool to evaluate the technical feasibility of a micro-grid with a constant load, this represents only one given loading situation. In reality, power system networks have load factors that are less than 1, and so there can be considerable variation in the load over the course of the day and on a seasonal basis. This would especially be the case for small micro-grids that have little diversity of load. What the power system planner needs to know is the probability that the present stand-alone system with its resource and forced outage rates will be able to meet the load on a daily, weekly, monthly, and annual basis considering all of the usual load variations that occur. In other words, what is the expected number of days during the year that the installed system capacity will be insufficient to meet the load?

Table 2-7 illustrates an instance of a weekly probability index evaluation (chance of not meeting the daily peak load) for the system with 10 plants. The variations in daily peak load in a week are shown in the table. The system capacity is assumed to remain constant at 100 kW. The interpretation of the cumulative number means that on an average, the system will not be able to meet the load 0.5 times per week (about once a week). This might seem like poor performance; however, if the micro-grid normally operated in parallel with the utility system and only transitioned to islanded operating during bulk supply outages, then this level of reliability might be sufficient on a statistical basis to meet the needs of the system during most outages and the generation deficit would go unnoticed most of the time. On the other hand, if the micro-grid was a fulltime stand-alone system, then a once-a-week outage would probably not be satisfactory and the generation sizes would need to be increased to improve the reliability. There are also load-shedding options that can be deployed so that most of the loads on the system can continue to operate in the advent of a slight generation deficit rather than dumping the whole system.

Table 2-7
Weekly Probability Index Based Upon 10 Plants with 10-kW Units and Daily Peak Load

Day	Peak Load (kW)	Loss of Generation Needed to not Meet Peak Load (kW)	Probability of not Meeting the Load
Sunday	30	70	0.000000
Monday	95	5	0.401263
Tuesday	85	15	0.086138
Wednesday	75	25	0.011504
Thursday	65	35	0.001028
Friday	55	45	0.000064
Saturday	45	55	0.000003
		Total System Capacity = 100kW	Cumulative Probability Σ = 0.500000

There will be an optimal number of generation units from a reliability standpoint. The use of too few units decreases the reliability, and the use of too many units can decrease the reliability too due to the fact that as the number of units increases, the probability of any single unit failing increases. If failure of any one unit, regardless of size, leads to a total micro-grid shutdown, then the reliability has actually decreased. This is why the most reliable system of the six studied in Figure 2-22 is not the one with 100 generators, but rather the system with 25 generators.

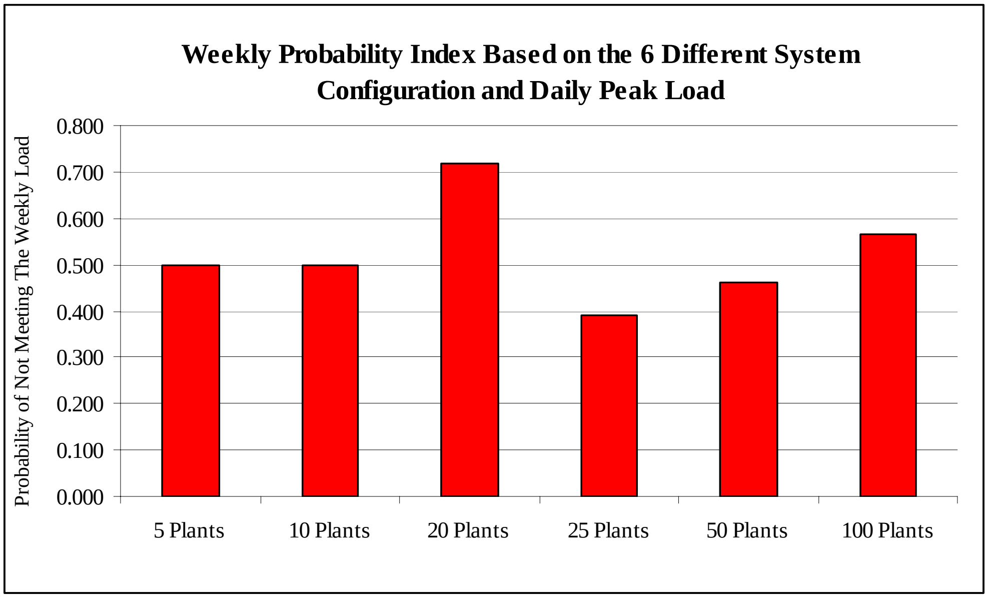

Figure 2-22
Probability of not Meeting the Weekly Load for the Six Systems Analyzed

Optimal Number of Generators from a Reliability and Cost Perspective

The optimization problem to balance cost against reliability is to tradeoff the number of units versus the cost of each unit and the reliability level of the overall system. As suggested in the earlier sections, a system with a large number of smaller units will generally be more reliable than a system with a small number of large units (with the exceptions just discussed in the preceding section). However, one disadvantage of using a large number of smaller units is that the per-unit price of each unit increases as the plant size decreases. In other words, the per-unit cost of ten 1-kW systems will be higher than the cost of one 100-kW system.

A method that evaluates the variations of per-unit price ($/kW) of a plant as a function of the number of plants, which was proposed in [1], is used to illustrate this trade-off concept. The equation used for cost estimation is shown in (2-2), which was derived based on the assumption that the price of individual plants, P, decreases by a certain amount every time that the individual size of units is increased; after that, the price remains constant. Symbols P_S and P_L denote the price of small plant sizes ($Size_S$) and large plant sizes ($Size_L$), respectively.

$$P = \begin{cases} P_L & \text{when} \quad Size \supset Size_L \\ D + E\ln(Size) & \text{when} \quad Size \subseteq Size_L \end{cases}$$

$$\begin{aligned} &where \\ &D = P_S - E\ln(Size_S) \\ &E = \frac{(P_L - P_S)}{\ln(Size_L / Size_S)} \end{aligned} \tag{2-2}$$

Figure 2-23 illustrates the variation in price (P) as a function of the number of plants in the system. In order to be consistent with the prior example (as demonstrated earlier in this chapter), $Size_S$ and $Size_P$ were taken to be 1 kW and 100 kW, respectively. It was assumed that the price of the smaller (P_S) and larger (P_L) plants were 2500 and 800 (\$/kW), respectively. It is clear from this figure that a large number of smaller plants are more expensive as compared to a smaller number of larger plants.

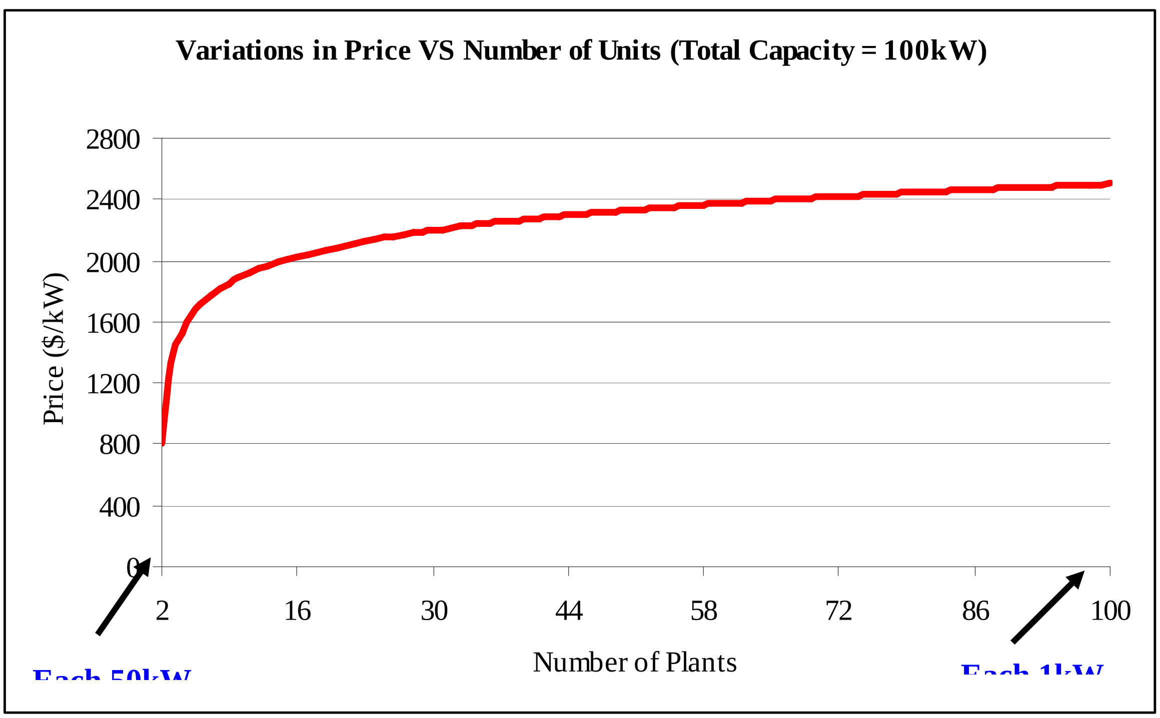

Figure 2-23
Cost Estimation as a Function of Number of Plants

3
CONTROL, OPERATION AND EQUIPMENT NEEDS OF MICRO-GRID SYSTEMS

Overview

The preceding chapter focused on the general architectures for various micro-grid configurations. This chapter is a more focused discussion of the specific control, operation and equipment needs for micro-grid systems.

While a key objective in developing practical and cost-effective micro-grid systems will be to use, as much as possible, the existing power system designs and equipment (such as switchgear and voltage regulators) that have been used for conventional power systems, it is clear that micro-grids have special needs in their protection and control that make it necessary to adopt new design approaches and, in some cases develop new specific devices to facilitate the operation of the micro-grid. Some of the key issues that must be considered for micro-grid designs include the interface and protection requirements for micro-grid generators, voltage control, load sharing, frequency regulation, stability and recovery of the system from blackouts.

Micro-Grid Interface Requirements for Generators

Distributed generators must be interfaced to the micro-grid system in a manner that facilitates safe and reliable operation. In addition, the generators must operate in a manner that facilitates proper voltage regulation, frequency control, and power quality conditions on the micro-grid.

Unlike ordinary distributed generation that interface to a conventional power system and normally must deal with only one mode of connected operation, micro-grid–based generators have the added complication that they must function in an environment where the system could be operating in several different modes and be changing significantly in its configuration. Examples of some micro-grid modes of operation include:

- Parallel operation with a strong bulk utility system
- Parallel operation with a weak bulk utility system connection
- Operation as the only source on a fixed, micro-grid island
- Operation as one of many dispersed sources on a fixed, micro-grid island
- Operation on a dynamically changing micro-grid island

These modes of operation represent most of the modes that can occur. However, some other possible modes exist. Figure 3-1 shows graphically these scenarios. These are all considered to be AC systems. DC interconnection is different and is discussed later.

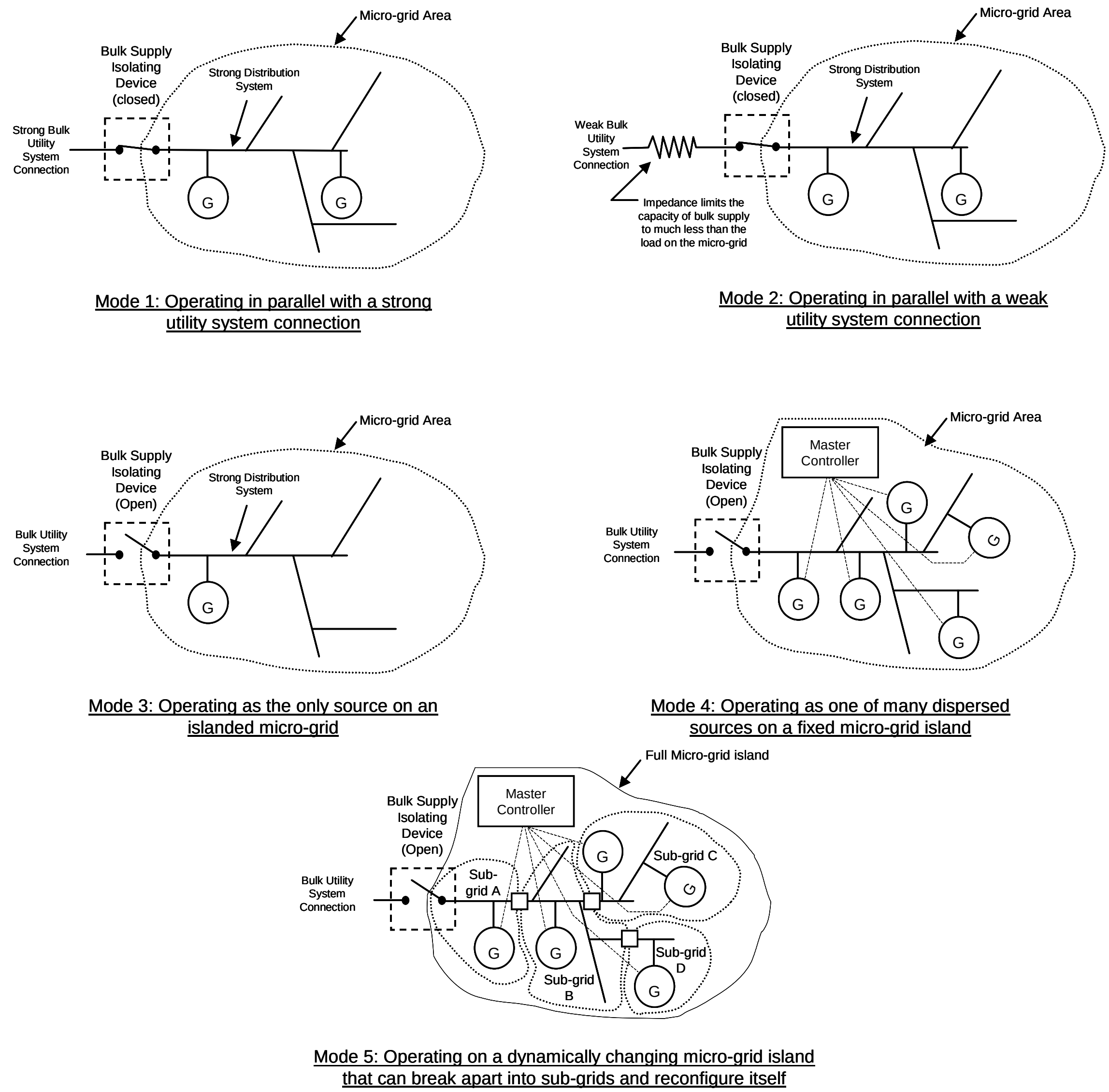

Figure 3-1
Possible Modes of Operation for Micro-Grids

For each of the modes shown in Figure 3-1, the interconnection and control equipment for the generators is required to behave differently. This is why it is important to understand the intended modes of operation for the micro-grid design and develop suitable interconnection requirements that can handle all expected modes of operation. Note that some simple micro-grids may only operate in one or two of the indicated modes, whereas more complex and advanced micro-grids that can dynamically reconfigure themselves may operate in all five modes at one time or another.

Mode 1 - Parallel Operation With a Strong Bulk Utility System

This mode is essentially the classic mode of operation for *standard distributed generation* where the generator is not attempting to directly regulate voltage, control frequency, or impact the power system conditions in any way other than to inject power into the system (either as a local exporter or as a non-exporter that offsets load at the customer site).

The interconnection methods that have been developed for conventional parallel operation of distributed generation can be found in documents such as (1) The Institute of Electrical and Electronics Engineers (IEEE) P1547 interconnection standard that is currently under development, (2) the already accepted standard, IEEE 929-2000 for photovoltaic inverters, and (3) many other utility and state interconnection guidelines that have been developed. These guidelines are all based on the concept that the distributed generation will have a minimal impact on the bulk supply and only a small impact on the local distribution system because it is small compared to the capacity of the bulk system connection and the distribution system. Some key characteristics of this type of interconnection approach are:

- The generator operates in a voltage-following mode (not attempting to directly regulate voltage or hold voltage to a set-point)
- The generator has anti-islanding protection that disconnects the generator if the generator becomes islanded with any portion of the distribution system or the voltage conditions leave the acceptable window of operation
- The generator does not attempt to regulate frequency but simply follows the system frequency

Of course, these operational characteristics are the antithesis of what is needed in the micro-grid when it changes from the *Mode 1 state* to one of the *islanded states*. During islanded operation, the last thing needed is for generators to trip if they should detect such an island. So protection needs to be established that allows generators to operate in parallel mode during conditions associated with normal utility system connection and under the guidelines of traditional DG interconnection requirements, but to transition to islanded control during that mode.

A way to achieve this transition is the use of anti-islanding protection at a defined connection point with the bulk system and separate protection packages on generators that allow islanding on the micro-grid. Inverters and other generators that have internal anti-island protection (such as that required in IEEE 929-2000) will not be suitable for most micro-grid systems unless their protection is modified.

Mode 2 – Parallel Operation With a Weak Bulk Utility System Connection

This mode of operation is a hybrid between an islanded system and operating in parallel with a strong utility connection. Here the micro-grid is connected to the utility system, but because of the weak nature of the connection, the micro-grid generators may be able to exert considerable influence on voltage and also could break free (break-out-of step) with the bulk system in the event of any stability problems brought about by a sudden perturbation on the system or generator control instabilities. On today’s standard distribution systems, every effort is made to avoid connecting an extremely large distributed generator to a weak system to avoid causing these types of problems. When such interconnections do occur, extra care is employed in the interconnection design and special equipment (such as additional regulator banks) is often needed to control voltage.

In the case of future micro-grids, a weak connection to the bulk system may be an intentional design feature so as to minimize the cost of transmission and substation infrastructure. In this arrangement, the micro-grid generation represents the bulk of capacity and is given responsibility for carrying most of the load. The bulk supply connection is used to support part of the load, to enhance reliability, and also to help stabilize the system. Because of the weakness of the utility connection, the generators on the micro-grid would need to take on some responsibility for voltage regulation and VAR control on the feeder and would need to be more carefully stabilized to maintain synchronism with the bulk power system. The bulk power system still would maintain frequency control.

Mode 3 - Operating as the Only Source on a Fixed, Micro-Grid Island

This is a common mode of operation for present day micro-grids where a single source (meaning one plant location that may be a single generator or cluster of generators in parallel) is employed that supports the operation of the micro-grid load. The micro-grid may be a factory, commercial loads, or campus-type situation with many loads. This arrangement is also consistent with the systems shown in Figures 2-3 to 2-7 in Chapter 2. Operating as an islanded system, the generator site has responsibility for voltage regulation, frequency control, reactive power control and generator and system fault protection. The bulk utility supply isolating-device (shown in Figure 3-1) has responsibility for detecting abnormal utility system conditions and separating the micro-grid from the bulk supply. The isolating device working together with the generator also has responsibility for reconnection of the micro-grid back in parallel with the bulk supply system. Because only a single generation site is employed, that site will be the master control for the micro-grid and load sharing between generators (if there is more than one at the generation site) can be performed locally using standard paralleling switchgear and exciter controls using techniques such as droop-governing or isochronous-governing methods. Communication and control between the generator site and the isolating device may or may not be needed depending on how the system is designed. Because of the use of a single generation site, this type of micro-grid operating as an island is really one of the easiest to control and protect. Protection methods can be radial based and operated essentially like a conventional distribution system. Significant field experience has been gathered on these systems because thousands are already in operation throughout the United States and other locations.

Mode 4 - Operating as One of Many Dispersed Sources on a Fixed Micro-Grid Island

This mode involves many sources operating in a generally fixed, islanded state. This type of operating mode is much more complex than the previous three modes discussed so far and is the type of micro-grid application considered for power quality parks. Here we have multiple generators with varying characteristics operating at many different physical locations on the micro-grid system. The interconnection and controls of the generators should allow these units to all work together in unison to provide optimal control of the system. The fault protection will be a combination of transfer trip and zone-based relaying techniques and generator load sharing (balancing) will need to be done by communication and feedback signals to all units. This type of interconnection and control is much more like that of a conventional, central station generating plant connected to the bulk power system.

Mode 5 - Operating on a Dynamically Changing Micro-Grid Island

This is the most complicated mode of all. Not only must the generators all work together to control voltage, frequency, VARs, and other parameters, as they do in Mode 4, but they must also do so in an environment where the micro-grid may be periodically reconfiguring itself by attaching itself to adjacent micro-grids or breaking apart in smaller micro-grids. This will require the highest level of communication between generation devices and the ability of the system to have the adaptive command and control whereby overall grid command and control may shift from one controller to the next as the system changes state. The generator protection schemes and operating set-points will have to adapt each time the system changes state. This approach is essentially a futuristic mode of operation that needs considerable research and development to implement effectively. It is not something that is done today intentionally.

Elements of Generator Interconnection on an AC Micro-Grid

The key elements of a distributed generation interconnection to an AC micro-grid are shown in Figure 3-2 and include a high-side overcurrent protection device protecting, a high-side disconnect switch (sometimes omitted), the step-up transformer, low-side disconnect switch, low-side overcurrent protection, and the generator/micro-grid protection relays. A local controller is shown that controls the engine throttle, excitation and other operating parameters. In the case of micro-grids with multiple resources, there also can be communications with a remote master controller that talks to all other generators on the micro-grid and facilitates optimal dispatch of the system. This control is also needed to regulate the excitation and generator throttle to allow for proper voltage and frequency control.

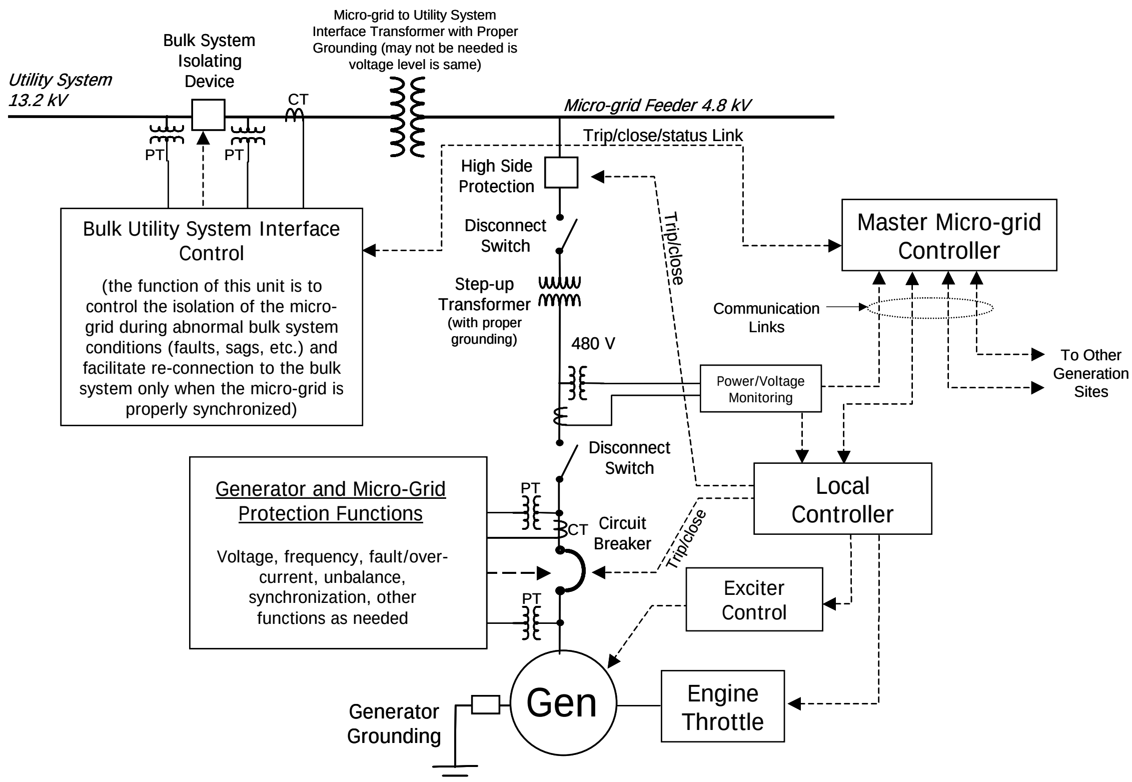

Figure 3-2
Key Elements of a Micro-Grid Generator Interconnection on an AC System

From the perspective of system grounding, the generator should be appropriately grounded in accordance with the wiring designs of the micro-grid (Is it a three-wire, ungrounded or four-wire, multi-grounded neutral?). Proper grounding also requires use of the proper interface transformer. Note also that unlike most standard distribution systems that are four-wire designs, the micro-grid may prefer a three-wire, ungrounded design for its high-voltage feeder because that can help simplify protection of all the generation sources. Note in Figure 3-2 that an interface transformer between the micro-grid and the utility system was employed. This may or may not be needed depending on design issues. In this case, it was needed because the primary voltage of the micro-grid was 4.8 kV and the primary of the bulk supply was 13.2 kV. Also, the transformer can serve as a grounding interface to change from four-wire, multi-grounded neutral systems to three-wire, ungrounded systems or vice versa.

Another key element of Figure 3-2 is the bulk-system isolating device. This is not a part of the generator interface itself, but it is critical to the overall operation micro-grid system. The bulk-system isolating device serves at the demarcation zone between the micro-grid and the standard bulk power system. It has protection to ensure that the micro-grid disconnects from the bulk system during abnormal bulk power system conditions or when requested by the micro-grid system controller. This device also ensures that synchronization is achieved before reconnection of the micro-grid to the bulk utility system. The bulk system isolating device will need to be an extremely fast-responding device if the power quality impact of bulk system voltage sags and interruptions is to be limited on the micro-grid. Use of a fast-acting static switch at this point can essentially minimize the perturbations that get through to the micro-grid.

The generator and micro-grid protection functions shown in Figure 3-2 must be carefully coordinated with the bulk utility system interface control to ensure that the micro-grid can transition from the utility system parallel mode of operation to the islanded mode. The bulk utility system interface will employ voltage and frequency relays and perhaps reverse power or directional overcurrent relays to quickly determine that the abnormal conditions (for example, a fault or voltage sag) have developed on the bulk supply. The voltage and frequency trip thresholds for the bulk-system isolating device should be tight (for example, approximately ±10 percent greater than or less than nominal voltage and operating within a few cycles, and a ± 1 percent or less for frequency and operating after 5-10 cycles of delay), and those for the micro-grid generator can be slightly wider and have longer time delays (many seconds). This ensures that the micro-grid separates from the utility system before the generators on the micro-grid start to trip. The generators on the micro-grid will need to have the capability to pick up a large amount load at the moment the bulk utility system is disconnected – otherwise the micro-grid voltage will collapse and it will not successfully ride through the transition to islanded mode.

If the micro-grid does drop out during the transition, the generators need to have the ability to restart a dead micro-grid. This means riding through inrush and cold load pickup if the grid has been down for some time. Also, black-start capability is needed, which means that battery power supplies or some other source is needed to start the generation and keep the controllers power up during any system outages. Load shedding and sectionalizing capability of the micro-grid may also be needed to restart the micro-grid up one section at a time if the inrush and cold load pickup is too much to pick up all at once or if no one source on the micro-grid has enough capacity to start the system.

From a control perspective, while the generator is running in parallel with the utility system, the master controller will be operating in a bulk system parallel control program mode. The instant that the bulk-system isolating device opens, it needs to send a signal to the micro-grid master controller to ensure it changes to the islanded control algorithm where frequency and voltage are controlled directly by the generators and perhaps key voltage regulator devices intended for utility-connected operation are disabled or changed to a compatible status.

Interface of Distributed Generators to a DC Micro-Grid

The equipment and controls needed for interface of generators to a DC micro-grid are somewhat different than their AC counterparts. One key difference is that because the system is a DC system, the concept of synchronization does not apply like it does with AC. Rather, to interconnect a DC source to a DC system, it is simply sufficient to match the voltage level between the source and the system. Secondly, because we are dealing with DC, transformers are not used as the final interface stage between the DC source and the micro-grid. Rather, devices such as DC-to-DC converters that are analogous to AC transformers but instead step up or step down the DC voltage are employed. Some of the more efficient DC-to-DC converter designs can be more than 96 percent efficient so losses are fairly minimal when that approach is used.

Shown in Figure 3-3 are two examples of generation sources interfaced to a 400-volt DC micro-grid. One example shows a three-phase AC generator that is rectified using a six-pole diode bridge and fed into a filter to smooth it to an extremely clean DC power. The other example shows a DC source (a fuel cell or PV array) that is fed into a DC to DC converter stage that provides voltage regulation control and matching of the DC source output to the required micro-grid input voltage. For the AC generator system, control of the voltage and power is by excitation and throttle adjustments on the generator. Another technique that could be employed to control voltage is by using a six-pole SCR bridge instead of the diode bridge and adjusting the firing angle. Both examples use an interface circuit breaker to control interconnection to the micro-grid and also to protect against abnormal system conditions. This interconnection switching function could also be done with solid-state devices and fuses in smaller generators. Not shown on the diagrams are the zone-based relaying schemes that would likely be applied at the interface circuit breaker—the circuit breaker would need to see out into a certain region of the micro-grid and coordinate with other generator protection zones (see also the flow control at end of this chapter). In addition to the local protection functions controlling the circuit breaker, the master system controller that is remotely located might also control the circuit breaker.

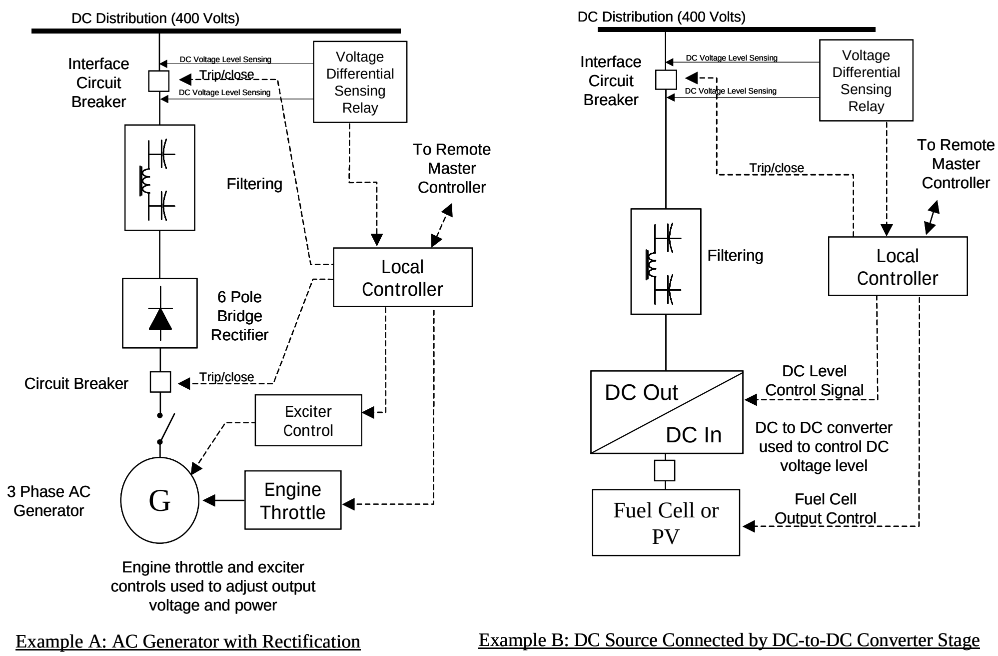

Figure 3-3
Interface of Two Types of Generators to a DC Micro-Grid

Voltage Control of Micro-Grids

Adequate voltage regulation of the power systems is necessary so that customer loads operate satisfactorily and the power system itself operates safely. The American National Standards Institute (ANSI) C84.1 standard specifies that voltages delivered by *conventional* power systems to the customer's point of common coupling (as measured typically at the service entrance or meter) should be within ±5 percent of the system nominal voltage rating. For a 120-volt nominal voltage, this is between 114 and 126 volts. This is known as the *Range-A* service voltage requirement. Occasional excursions outside this limit are allowed to +6 and –8 percent of nominal, but the number of customers impacted and frequency of these excursions is to be limited. This broader range is referred to as the *Range B* service voltage limits.

The design objective for conventional power systems is typically that the system should deliver Range-A service voltage to the customers. Micro-grids are not conventional power systems and some differences may apply. For example, DC systems may be able to have a wider range of voltage because of the ability for local inverter devices to compensate at each load. Also, some micro-grids will be utilization-level systems in that the utility does not actually own or operate the micro-grid so the customer that owns the system may have more flexibility—perhaps using what is referred to as the *Range A and B Utilization Voltages*. Regardless of these issues, in general, it is probably good practice that most micro-grid planners will design the AC micro-grid system to deliver Range-A service voltage to each building load on the system. This section discusses some of the methods and control needed to regulate a micro-grid system to meet this objective.

On conventional power distribution systems, voltage is controlled and regulated using equipment such as load, tap-changing transformers (located at the substation), feeder step regulators, and switched capacitors. Various combinations of these devices work in concert to take the voltage levels delivered to the substation by the transmission system and then control the voltage profile on the distribution circuit so that most or all customers receive voltage within the ANSI Range-A limits at their meters.

Micro-grids can use some of the same devices and methods used for conventional power systems, however, because of the presence of local generation, and especially when operating in the islanded state, methods of voltage control must be employed that use the generators themselves as a key part of the control and also the methods must be able to deal with micro-grid architectures that have bi-directional flow.

Not all micro-grids have bi-directional flow architectures. Some, such as the examples in Figures 2-2 to 2-7, are radial distribution systems energized at the "front-end" feed point. For these systems simply controlling the output voltage of the generation site (by excitation methods in the case of synchronous generators and inverter pulse width modulation methods in the case of voltage source inverters) should be sufficient to act much like a load tap changing transformer action in a substation. Farther down the feeder, conventional, step-voltage regulators and switched and fixed capacitors may be employed as needed to maintain adequate voltage. The voltage profile in this example would be similar to that on a conventional, radial distribution system and the techniques, and step regulator settings probably could be coordinated in a similar fashion to those of a conventional distribution system (see Figure 3-4).

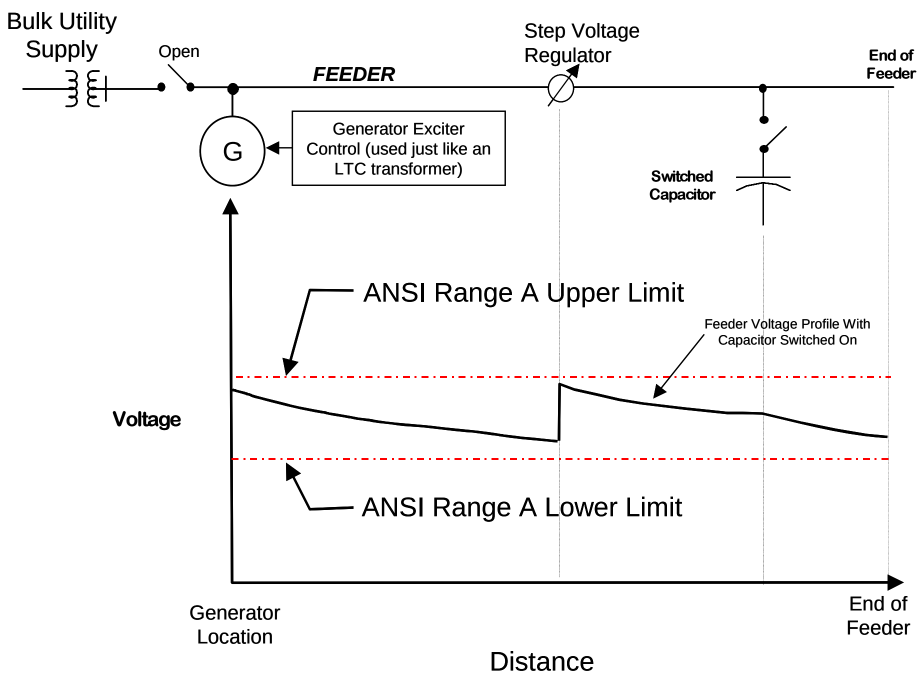

Figure 3-4
Voltage Regulation on a Radial Micro-Grid Circuit with a Single Generation Source at One End

Another type of micro-grid system that has been discussed is a system with multiple generation sources dispersed throughout the grid and coordinated from a central location (such as the system of Figure 3-5). For this system, the radial regulation approaches described earlier would not work properly because it would be difficult to regulate voltage and balance load amongst all of the machines at the same time without central control. The best approach from a feeder loss and voltage regulation perspective is to set the operating states of the machines so that they satisfy the loads (real and reactive on either side of them) up to the load center point for each line section between machines—however, this may not yield good economic performance of the machines depending on the load levels and load distribution on the feeder.

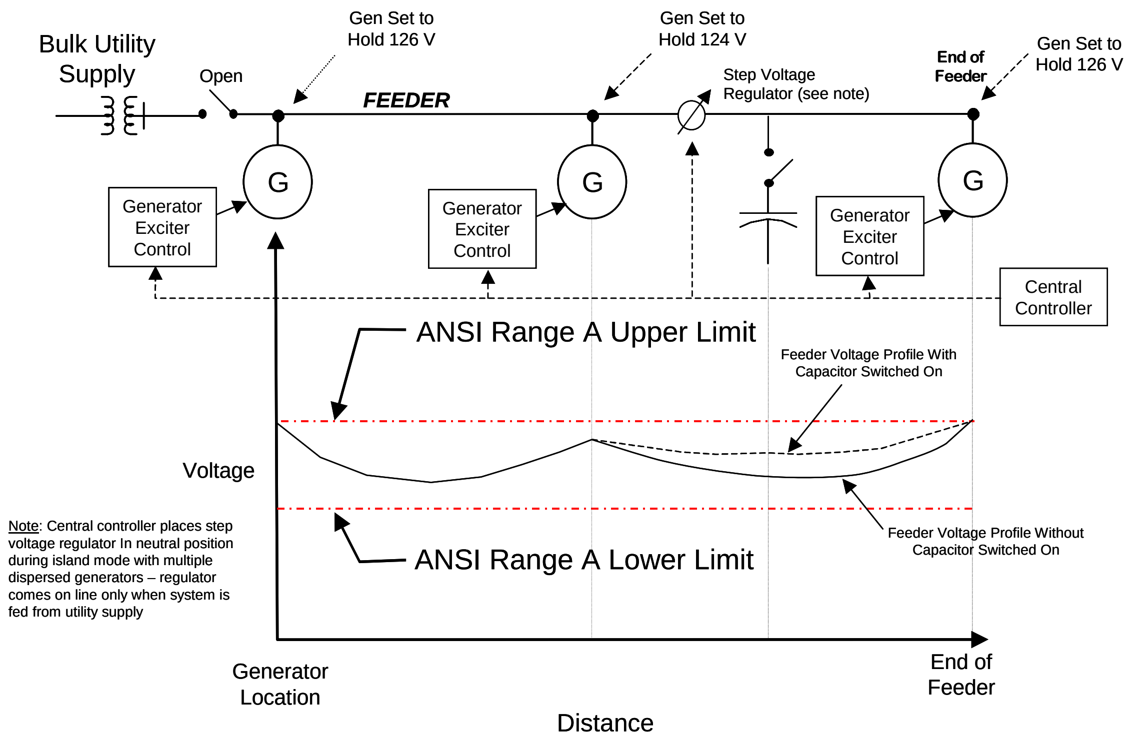

Figure 3-5
Voltage Profile on a Micro-Grid with Three Synchronous Generators Coordinated by a Central Controller

To regulate voltage, the generators are employed with excitation and throttle controls that allow the real and reactive power output to be properly controlled to keep voltage within acceptable limits. Communication to a central controller helps to ensure that the generators can properly adjust themselves to share load (reactive and real) and maintain an adequate voltage profile. The control makes the decision as to the best balance of economic performance of the generation versus ensuring good voltage regulation on the feeder. This involves measuring the output levels of the machines, and sending this information back to a central location where the information is processed and command signals are then sent back to the machines to balance loading. For the machine in the center of this example, the power flows in both directions need to be known. Note also that the regulator has been commanded to operate in a neutral position during this mode of operation but could be brought into action if needed by the master controller—for example, if the system reverts back to a utility system front-end fed feeder. The impact of the switched capacitor on the voltage profile is shown in the example for illustration purposes.

The examples of Figures 3-4 and 3-5 employed generators that could control their real and reactive output by varying the excitation level and throttle settings. This is important because any generators that are intended to help control the voltage should be designed to control both real and reactive power flows. Energy sources with a fixed reactive power output or power factor cannot fully participate as the primary means of voltage regulation of the power system. Many distributed generation sources that are becoming available now have controllers that operate only at a fixed power factor—they are intended for parallel operation with a bulk utility system in a "voltage-following mode" but not for strong participation in system voltage regulation. They are being developed to operate this way because the industry is focused on conventional distributed generation that is not intended for micro-grid support. It is satisfactory to have some voltage following resources on a micro-grid, but they will need to be limited to a fraction of total capacity.

Non-rotating, micro-grid sources and even some rotating energy sources such as micro-turbines will probably be individually connected to the grid by a self-commutating bridge circuit (an inverter). A self-commutating, voltage-controlled converter can vary its output to regulate the AC voltage and a self-commutating, current-controlled converter can usually vary its AC reactive power output to control AC voltage. These devices may in fact control voltage better than a synchronous generator because their inherent time constants are not as large. To provide for this mode of operation, new controls will be needed that are not based on voltage-following approaches and the rating of the bridge may also have to be increased slightly to accommodate the additional reactive current. Because the reactive current is in quadrature with the active current, the overall rating increase is less than additive; it is found using the Pythagorean theorem. A reactive power rating (generation and absorption) approximately equal to 50 percent of the active power rating can be provided for only a 12 percent increase in the converters overall MVA rating.

In a conventional, high-voltage transmission system, the series resistance of a line or cable is normally much lower than the reactance. Because this is true at moderate levels of loading, the active power flow is almost entirely dependent upon the difference in the voltage phase angle across the line, and the reactive power flow is almost entirely dependent upon the difference in the voltage magnitudes at the two ends of the line. Power system control devices may take advantage of this at the transmission level. For example if voltage is low, then switched shunt capacitors, which produce only reactive current, may be turned on to boost the voltage.

Micro-grids will operate at the distribution system level. At this level, the line, because of the tighter spacing between conductors and smaller wires employed, has a series resistance that is more comparable to the series reactance and may even exceed it at some locations. Thus, both real and reactive current injections from sources can have a significant impact on voltage at the distribution level. The real current injection will have the least impact on voltage at the substation (where the reactance of the system dominates) and the most impact on voltage at the ends of long distribution lines with small conductors (where resistance is high relative to reactance). On distribution systems, Micro-grid control systems need to consider both resistance and reactance effects on the distribution system voltage and so sources that inject only real power will impact the voltage—even if they are just voltage following.

In some cases, the micro-grid system with only current-controlled sources may have extremely short circuit line lengths, so resistance and reactance of the lines will be fairly small. In this case, the load will almost entirely determine the systems current versus voltage characteristic. A purely resistive load can draw no reactive power so if a system has only a resistive load and no distribution system resistance or reactance the only reactive power flows will be exchanges between sources. The reactive power flow between sources will have no effect upon the voltage at the resistive load, but there will be a one-to-one correspondence between active power and voltage. A current-controlled converter that tries to change the voltage magnitude by varying its reactive power output is therefore doomed to failure in this case. This may have to be considered in tuning and designing a micro-grid system and its control architecture. Series reactors or transformer leakage reactance may increase the reactance of micro-systems so the normal power flow approximations still work.

In other cases, the micro-grid distribution system may intentionally be designed to be extremely weak (as was discussed in the case of Chapter 2 for the low voltage micro-grid) and then the impedance of this type of system would be quite high. In this case the reactive and real power flows across the wires could have too strong of an impact on voltage and could lead to serious low or high voltages on the network depending on the conditions that exist.

Micro-Grid Voltage Regulation and Reactive Pattern Patterned after Traditional Transmission Systems

Voltage-Controlled Converters (Inverters)

Voltage-controlled converters connected to a micro-grid through a reactor or transformer could be controlled as follows to regulate the micro-grid voltage:

Use the difference between an assigned reference voltage and the measured value of voltage on the grid side of the connecting transformer or reactor for the voltage regulator input. This input acts on a proportional controller (or an integral control if suitable current compensation is also used) to vary the output of the voltage regulator. Additional control paths enforce current limits and implement other control refinements. The output from the voltage regulator is a set-point voltage used by the pulse width modulation.

The pulse width modulation is programmed to generate a voltage whose magnitude is equal to the set-point voltage.

If more than one source connects to the micro-grid at the same location, the measured voltage may have to be current compensated or cross current compensated so the reactive power is shared equitably between the two sources. Other control refinements borrowed from STATCON and SVC technology might also be included in the bridge control:

To coordinate with slower-acting, switched shunt compensation a slow-acting control loop might effectively change the voltage regulator reference to get the level of reactive power wanted for steady state operation. Slower-acting devices such as switched shunt reactors and capacitors would then respond to regulate voltage letting the micro-grid source keep its fast-acting, reactive power capability in reserve for disturbances. A master-slave arrangement can also be used within a system that is otherwise patterned after traditional power system control to coordinate reactive power devices at the same location.

When voltage is extremely low, such as during a system fault, the normal control might be overridden to force the reactive current output of the bridge to zero. This would be done so the device does not contribute to momentary over-voltages when system faults are cleared.

Current-Controlled Converters

Current-controlled converters could be programmed to inject reactive current into the micro-grid to help control voltage. A voltage regulator similar to that described for the voltage-controlled converter would be designed to increase/decrease the reactive current injection when the voltage is lower/higher than desired. Current-controlled converters at the same location could be crosscurrent compensated to share the reactive power loading equitably.

Micro-Grid Voltage Regulation Using a Master-Slave Control Strategy

Micro-grids that employ multiple generators paralleled at a single site may use a master-slave strategy to control voltage. One of the reactive-power producing devices, the master, would be adjusted to control voltage and the other reactive power sources would base their reactive power output level on the output of the master source. This strategy requires communication between the source devices so it is usually not suitable for a dispersed system. Special provisions would have to be made to seamlessly handle the situation where the master source has its output curtailed for some reason or is intentionally or unintentionally taken out of service.

Synchronous Generators

A synchronous generator that is designated as the master source would have a voltage regulator that responds to a voltage error signal to adjust the generators excitation level. Synchronous generators that are designated as slaves would have excitation systems that fix the reactive current output of the generator at a level that is based upon the output of the master source. Excitation systems capable of performing both functions are commercially available.

Voltage-Controlled Converters

A voltage-controlled converter that functions as the master controller may be directly connected to the micro-grid if it is the only voltage-controlled converter. Otherwise, it will need to be connected through a reactor or transformer with a suitable leakage reactance. If it is connected directly to the grid, it may just be programmed to produce a voltage of the desired magnitude and frequency. If it is connected through a reactor or transformer, its voltage set point may be current compensated so it holds a fixed voltage on the grid side or it might use feedback control with a voltage regulator that responds to a voltage error signal based upon the measured voltage on the grid side to adjust the bridge-side AC voltage magnitude.

The voltage-controlled converters that function as slaves would be connected through a reactor or transformer with a suitable leakage reactance. Their reactive power set point would be based upon the reactive power output of the master source. Each slave voltage-controlled converter would have a feedback controller that uses the difference between its reactive current set point and the actual reactive current output as an input error signal. The controller output would be used to adjust the magnitude of the AC voltage produced by the bridge to get the desired reactive power output.

Current-Controlled Converters

A current-controlled converter that functions as the master source would have a feedback controller that uses the difference between the local grid voltage and the desired voltage as an input error signal. The controller output would be used to adjust the magnitude of the reactive current produced by the bridge to get the desired voltage. If the micro-grid uses only current-controlled converters and has only resistive load, the reactive power can only circulate between sources and will not have the desired effect on voltage.

The current-controlled converters that function as slaves would set the level of their reactive power output based upon the reactive power output of the master.

Frequency Control and Balancing Load and Generation in Micro-Grids

The controllers that are presently used for many of the energy sources that are being considered for distributed generation are normally designed to maximize the efficiency or energy output from the device itself and to regulate the internal energy source voltage. Different control objectives will need to be satisfied in micro-grids applications and the percentage of energy sources that do not participate in satisfying these new control objectives will have to be strictly limited. This will mean that most of the micro-grid energy sources will no longer be programmed to return to the operating point that maximizes their individual performance. In fact, most energy sources probably will not be able to stay at their most advantageous operating point even during normal operation. For a micro-grid as a whole to be reasonably reliable, it will be necessary to keep enough generation in reserve to make up for at the loss of the largest source or the loss of any power interchanged with an outside system. This will probably mean that many of the sources will normally need to run only partially loaded.

In traditional power systems, energy is drawn after a disturbance from the rotating inertia of generators and prime movers to satisfy the load and limit changes in frequency until the speed governors and prime movers can respond to provide more/less energy. At rated speed, enough energy is stored in the rotating inertia of a turbine and generator to supply the rated power for approximately 4 seconds. Many of the energy sources that may be used for micro-grids are not rotating devices so another source of stored energy must be provided to balance the load until the energy-producing sources can respond. The shunt capacitor on the DC side of a power converter is a source of stored energy used by non-rotating sources, which is in some way equivalent to the rotating inertia of a generator. However, typically, at rated voltage, only enough energy is stored in the capacitor to supply the rated power for approximately 0.02 seconds. In micro-grids powered largely by non-rotating sources, additional energy storage will probably be needed to satisfy the load immediately following a disturbance or for frequency control.

Energy storage devices may be used to temporarily replace the lost power after a disturbance but some combination of energy-producing sources will ultimately be needed to increase power output to permanently replace the lost power output and maintain system frequency. If the response of the energy producing sources is fast and/or the power outage is small, less energy storage capacity will be required to satisfy the load and control frequency. An example of an energy storage device that can be used to stabilize the system during fault disturbances and during dynamic variations in load is the dynamic stabilizer shown in Figure 3-6. The dynamic stabilizer concept employs a four-quadrant inverter with ultra-capacitor energy storage. It can rapidly discharge or charge depending on whether the system is accelerating or decelerating. It can be used to mitigate variations in both system frequency and voltage during typical disturbances and load steps.

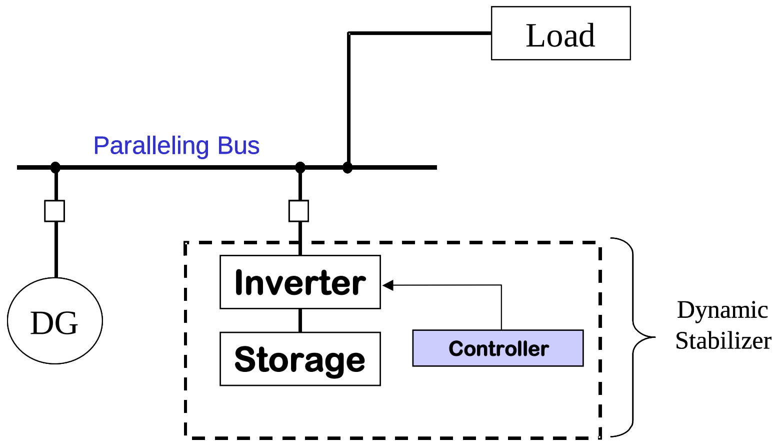

Figure 3-6
Dynamic Stabilizer Using Ultracapacitor Energy Storage

One way to limit frequency excursions following outages is to minimize the size of the outage. This could be done by using many small power sources configured so no credible single event can disable more than one source or divide the micro-grid into separate, power-rich and power-poor regions. Power interchanged between the micro-grid and other systems must also be limited for this approach to be effective. If the power outage can be kept small, less reserve energy will be needed and less storage capacity will be required to control frequency.

The North American, interconnected power systems have extremely tight frequency control. This is because they are so large that no single event can remove or disable a significant portion of the generation. Other parts of the world, notably third world countries and island nations, are able to operate with much looser frequency control. It is therefore probably possible to operate micro-grids with much looser frequency control than we now use in North America. Less reserve source capacity would then be needed and it would be possible to use larger, slower-responding power sources.

Impact of Distributed Resource Type on Load Sharing and Frequency Control

Frequency control in a power system should normally be a joint effort with as many generators and loads participating as possible. The following discusses the ability or inability of various energy sources that might be used in a micro-grid to participate in the control of the electrical frequency. Some considerations are:

- Is the power output controllable?
- If so, how fast can the power output be changed?
- How much stored energy is available and how fast can it be accessed?
- Are better designs likely to be forthcoming?

Reciprocating Engines

Generators driven by reciprocating engines are commercially available with suitable governing systems and excitation systems for micro-grid applications.

Micro-Turbines

A micro-turbine generates power at a high frequency and a back-to-back DC converter converts the high-frequency power output to the power system frequency. The micro-turbines presently available are not configured to participate in power system frequency and voltage regulation. This is, however, an extremely new technology and it seems likely that suitable controls for micro-grid operation could be developed when they are needed. The existing speed and power control designs vary with the manufacture and specifics are not available. The control architecture described here therefore does not represent a specific manufactures equipment but is intended to describe the general characteristics of existing equipment.

When a micro-turbine is grid connected, a pulse width modulated bridge on the network side acts as a current source to supply the specified power at unity power factor. The bridge that is connected to the turbine is also pulse width modulated and controls the DC voltage. Because no energy is being stored in the DC capacitor during steady state operation, the power demand of the ac system is passed to the turbine. The fuel is controlled to keep the exhaust temperature at the optimum level to maximize efficiency. In steady state operation, for given ambient conditions, the exhaust temperature and the turbine power output uniquely determine the turbine speed. A one per-unit change in power takes approximately 30 seconds. The immediate (first second) response to an increase in fuel may actually be to decrease in the power delivered to the shaft because the fuel-to-air ratio is not optimal and the compressor uses more of the available energy to increase the air flow. The stored energy provides little short-term support. When the micro-turbine is operating isolated from a power system, a battery may be connected to the DC converter bus to provide short-term capability but at least some manufactures do not use the battery when the micro-turbine is grid connected. The micro-turbine that we are testing has difficulty picking up loads. When load is dropped the turbines use a dump valve to help control speed.

If micro-turbines are applied in micro-grids, they should be equipped with governors that vary the power set point to help pick up load after a disturbance and participate in the AC system frequency regulation. It will also be necessary to provide some fast-acting source of energy to pick up load and reduce frequency excursions immediately after a power system disturbance. The rotating inertia of a micro-turbine at first seems to be relatively small compared to its power output. However, because micro-turbines and their generators typically rotate at nearly 100 kilohertz, the stored energy is significant. Power system frequency dips could be reduced if the back-to-back converter controls and the turbine can be designed so the energy stored in the rotating inertia can be accessed following an AC system disturbance. A small flywheel rotating with the shaft might be a cheap way to provide even more energy storage that can be quickly accessed to help pick up load and reduce micro-grid frequency excursions. The per-unit inertia, H, of a 1 pound mass, 8 inches in diameter, and rotating at 100 kilohertz is approximately 4.3 on a 30 kva base. This is approximately the same as the per-unit inertia of the shaft train of a large steam turbine expressed on its kVA base.

Small Hydro

Governing hydro generation that is attached to a micro-grid should not be much different from governing hydro generation that is attached to a normal power system. When the gate is opened to increase water flow much of the energy is initially used to accelerate the water in the penstock. The energy available to drive the generator therefore decreases momentarily until the water gets up to speed. The power output from the generator will of course exceed the original level after the water accelerates. This phenomenon is well understood and must be considered in selecting a governor.

If a suitable site is available, there may be a temptation to use a relatively large hydro facility in a micro-grid. As indicated in the “Frequency Control and Balancing Load and Generation in Micro-Grids” section, the proportion of the generation that can be dropped by a single event needs to be limited to maintain reliability and to have adequate frequency regulation.

In some hydro sites, the impounded water provides a significant amount of stored energy, which can be accessed to generate additional electrical power in less than a minute if the generator is not already fully loaded. The hydro generators might also be used as motors to pump water up hill when the micro-grid has surplus generation so the energy can be used when there is not enough other generation available.

The rotating inertia of a hydro generator also provides stored energy that can be accessed to reduce electrical frequency excursions in the first seconds following a disturbance. A hydro plant can even be built so the generator can be operated as a synchronous condenser when it would not otherwise be in use. The energy stored in the rotating inertia can then help limit frequency excursions even when the unit is not producing power.

Fuel Cells

The power output of fuel cells is of course controllable, but the reported speed of response for fuel cells varies considerably (anywhere from a minutes to milliseconds to go from zero to full load) and only part of the rated output may be available quickly. In one system approximately 15 percent of the capability is available in a second, but it takes minutes to get additional output. This, of course, depends upon the technology employed for fuel conversion. Details are not available on how the fuel input and the AC side electrical output are coordinated and this probably varies with manufacturer. For synchronous operation with an AC system, it is likely that the inverter varies its firing to maintain a specified constant level of AC active and reactive power and the fuel is controlled to maintain a specified DC voltage (fuel flow follows AC-power changes). To be effective as a primary power source in a micro-grid application, the speed of response to changes in the power order may need to be improved. Fuel cells are still in the early stage of development so improvements in the response speed are likely. A large capacitor on the DC side might also serve as an energy storage device if the fuel cell itself cannot be made to respond fast enough. To work in a micro-grid, the existing fuel cell controls will probably need to be augmented. A governor, which varies the power order to help control the micro-grid frequency without violating the devices capability, may have to be added and a voltage regulator that varies the reactive power output, subject to limits, to control the local micro-grid voltage may also be missing on most commercial units.

Solar

Solar panels produce DC power and use a controlled inverter to convert the power for use in the AC system. The amount of power that a solar panel collects depends upon the DC voltage applied to it. The converter can thus control the amount of power collected by a solar panel by varying the DC voltage. This however wastes the available power above the control set point. Solar collectors are thus not likely to be useful for frequency control or load balancing. Their use in micro-grids may therefore have to be limited. Not only is a solar collector likely to be unsuitable for regulating frequency, but its power output varies with cloud cover, so it will put an additional burden upon the other sources which must vary their power to control frequency. An oversized DC shunt capacitor that stores energy between clouds may help to reduce this problem and also help limit frequency excursions following system disturbances until other energy sources can respond.

Wind

Modern windmills rotate at the frequency that is best for capturing the wind's energy and use back-to–back converters or doubly excited generators to produce electrical power at the rated AC system frequency. Changing the blade angle can vary the power collected by a windmill, but to avoid wasting the available energy, the blade angle is normally adjusted to maximize the power output. Windmills are thus not likely to be useful for frequency control during period of heavy system loading. Not only is a windmill likely to be unsuitable for regulating frequency while the system is heavily loaded, but its power output varies with wind gusts so it puts an additional burden upon the sources that do vary their power to balance the load and regulate the electrical frequency. The installed windmill capacity in a micro-grid may therefore have to be limited, or large energy storage devices such as pumped hydro may be required to help balance load and generation, and control system frequency. An oversized capacitor on the DC side of the converter could also be used to store energy between wind gusts and to help limit frequency excursions following system disturbances until other energy sources can respond.

Because the energy from windmills is essentially free, they ideally will be the last units turned off during periods of light system loading. However, because of the power and frequency control issues mentioned above it may not be possible to use all the windmill capacity during periods of light system loading. It may then be desirable to run each windmill at less than maximum output varying the blade angles to help control system frequency and take out the dips and spikes in power output that are caused by wind gusts. This mode of operation may allow the windmills to produce a greater percentage of the power required by the system at light load.

Batteries

Battery energy storage may help provide short-term frequency control until slower energy sources can respond to system disturbances. Stand-alone battery installations with dedicated converters could be used to do this. Another approach would be to use batteries on the DC side of other bridge-connected devices. The dynamic stabilizer concept of Figure 3-6 used with batteries could play a role in helping to maintain system frequency. However, batteries are asymmetrical in that they can't be charged as rapidly as they can be discharged. This would make a given size battery storage system more capable of accelerating the power system than decelerating it.

Capacitive Storage

Capacitive energy storage may help provide short-term frequency control until slower energy sources can respond to system disturbances. Stand-alone capacitor installations with dedicated converters could be used to do this. Another approach would be to use oversized capacitors on the DC side of other bridge-connected devices. Capacitors can be a symmetrical technology from the perspective or charge/discharge rates and so a dynamic stabilizer equipped with ultracapacitors like that shown in Figure 3-6 would be capable of decelerating the system as fast as it could accelerate it. This makes capacitors an extremely balanced storage technology for that application.

Flywheel Storage

Flywheel energy storage may be used to provide some short-term frequency control until slower energy sources can respond to system disturbances.

So far, we have looked at the response characteristics of various energy sources. We will now look at options for coordinating the control of these devices to operate the network as a whole. Several micro-grid designs and control options might be used to achieve these objectives. Some of these options are discussed below.

AC Micro-Grid–Coordinated Control Patterned After Present Power Networks

This design would have the following attributes:

- Most electrical sources would be rotating sources or voltage-controlling converters. Transformers would probably be used to connect the sources to the grid
- The sources would be designed or controlled so the frequency of the voltage applied to the grid by the source increases when the power from the energy source momentarily exceeds the ac electrical power output to the grid. Synchronous machines are designed to do this. They have been cleverly constructed so the electrical frequency is linked to the mechanical frequency of the rotor. If the mechanical power exceeds the electrical power output the rotor accelerates[1] increasing the electrical frequency. Non-rotating energy sources would probably be bridge connected. The bridge firing would be controlled to create a sinusoidal voltage on the grid side whose frequency squared is proportional to the difference between the energy from the source and the electrical energy output to the grid. This difference in energy is of course also the energy stored in the shunt capacitor on the DC side of the converter. The frequency squared will thus also be proportional to the energy stored in this capacitor[2] and the frequency will be proportional to the voltage on this capacitor. Increasing the electrical frequency will of course over a period of time result in a larger electrical voltage phase angle. Because the impedance of the transmission is normally mostly inductive, an increase in voltage phase angle will result in more electrical power output to the grid. The electrical power output thus naturally increases until it matches the power produced by the energy source.
- Some electrical loads might also be designed to have a similar characteristic
- Most sources would use governors to raise/lower the power output relative to a set point when the electrical frequency is low/high
- A slower-acting dispatch function could be used to reapportion the power-producing device set points to optimize system security, minimize costs, and recognize thermal and energy limitations
- Most of the sources would also use a voltage controller to adjust the voltage magnitude. This control would also have a droop to promote reactive power sharing between closely coupled units and would recognize various equipment limits.

The Need for Governor Droop

The power from two parallel sources will not divide evenly if they are both controlled to precisely govern frequency. One source will think the frequency is slightly high and decrease its output and the other will think the frequency is slightly low and increase its power until one or both run out of range. One-way to prevent this is to effectively reduce the frequency set point with loading. Typically, the set point will decrease by 5 percent as the unit goes from zero to full load—this is known as droop.

[1] The per unit energy stored in the rotating mass of the rotor is $H*\omega^2$ where H is the per unit inertia of the rotating mass and ω is the per unit speed of the rotor which is also the per unit electrical frequency.

[2] The per unit energy stored in the capacitor will be $CV^2/2$ where C is the capacitance and V is the DC voltage. The energy in this capacitor is thus an analog to the energy in the mass of a rotating energy source.

Options for Controlling Electrical Power and Fuel

For some devices, the fuel flow may follow the electrical power output. The governor will control the inverter firing to vary the AC voltage phase angle (and thus electrical power output) directly. The fuel flow to the energy source would then respond to the decrease in energy in the DC-side shunt capacitor (or DC voltage). In such cases, the governor may need limits that recognize the power output capability and rate of change limitations of the energy-producing device so it does not demand more or less power than the device can deliver. Another approach (electrical power output follows the fuel flow) would be to have the governor control the fuel flow directly. When fuel is increased, the energy-producing device adds DC energy to a capacitor. The inverter firing is than controlled to keep the DC voltage constant by draining energy from the capacitor and delivering it to the AC system.

Frequency Control and Load Balancing

Frequency control and load balancing following islanding or the loss of a major source or load may be one of the biggest challenges for micro-grids. It will be necessary to have at least some sources on standby that employ rotating inertia, ultra capacitors, or other device that can provide electrical power quickly following a disturbance to limit electrical frequency deviation until slower-acting power sources can come on line. It may also be necessary to limit the size of the largest source and load and the amount of power that can be transferred while tied to another system. If this cannot be done, it will be necessary to accept outages when large sources, loads, and interconnections are lost. Similar limitations will of course also be present with other micro-grid designs but the closed loop frequency control included in this design, which must have a limited gain to be stable, may be less effective in dealing with a power mismatch attributable to an outage than other designs.

Phase Balancing

Traditional power systems generate and transmit three-phase power. The system is designed so the sinusoidal voltage waveform for each phase is 120 degrees ahead of the voltage for one of the other phases and 120 degrees behind (or 240 degrees ahead depending upon your point of view) the other. The same is true for the currents in the three phases. Many power system devices are designed to operate properly only if this relationship between the phase currents and voltages is precisely maintained. Low levels of unbalance will cause metering errors and motor derating and higher levels will cause thermal damage (rotor heating) and damaging overvoltages for phase-to-phase–connected equipment. Extremely little deviation from the normal phase relationship is therefore allowed. The internal voltages produced by three-phase generators are precisely in phase. Individual small utility customers, however, will normally take power from only one or two of the distribution feeder phases. To keep things balanced, the utility will make a conscientious effort to attach an equal amount of load to each of the three phases. The total load from several feeders coming into the same substation will be even more balanced by design and because of the law of averages.

A micro-grid may consist of only the load and distributed generation on a single distribution feeder. If such a grid is not attached to the utility network, it may be fed mostly by single-phase, distributed sources. There will, however, also be three-phase devices attached to the grid so it is critical that the normal three-phase relationship for voltage and current be observed. Keeping the proper phase-to-phase relationships with distributed, single-phase sources is not a trivial task. This task is even more difficult if the source frequencies are allowed to vary so the load and generation can be balanced by governor action without a centralized control. One approach would be to provide communication between three, single-phase converters to fix the relative positions of their sinusoidal voltage waveforms while allowing the common frequency of oscillation to increase or decrease. This obviously will work best if the converters are near each other. Another approach would be to provide a device that can transfer power between the three phases to balance the voltages. It is theoretically possible to do this using a static VAr compensator, SVC, a static compensator, STATCOM, or a rotating phase balancer but the cost may be high. A third approach would be to use almost all three-phase sources in the micro-grid.

Advantages

Patterning micro-grid controls after present power systems has many advantages. The technology would take advantage of almost a hundred years of power system experience and is therefore well understood. Nearby single-phase, voltage-controlled converters might be linked together in groups of three to emulate three phase-balanced sources; otherwise, no need exists for high-speed communication to coordinate the grid control. This architecture is also robust, so there is almost always no need to change the control structure or settings when devices are added or removed from the micro-grid. In many cases, existing equipment and equipment designs may be employed with this type of control. A micro-grid based upon this architecture should be able to disconnect from the AC system seamlessly if it is not exchanging too much active and reactive power before disconnecting. It may therefore be more reliable than the utility to which it is normally attached because it can continue to operate during most utility outages.

An AC Micro-Grid With Voltage-Controlled Converters and A Centralized Controller

This control system design might have the following attributes:

- Most of the electrical sources in the micro-grid would be static converters generating a specified voltage (magnitude and phase angle) at a constant frequency on the AC side. Transformers would be used to connect the converters to the grid. If the sources are at remote locations, the phase angles could be coordinated using a satellite signal. The frequency and reference angle might be based upon the utility voltage at the interconnection point whether or not the two grids are actually connected. Some provision would of course have to be made to generate a reference signal during utility outages and to resynchronize the signals when the utility recovers.
- A central controller would specify the voltage magnitudes and phase angles of individual sources relative to the reference. The central control would monitor the generation, network and loads to select voltage phase angles that produce the set point power outputs. The source

limitations would also be considered in selecting the voltage magnitudes and angles. A feedback system might be used to adjust for calculation error and correct the voltage magnitudes and angles if the intended flows are not initially obtained.

- The current flow from each source would initially respond to a fault much like a normal power system. Relatively high leakage reactances in step-up transformers may however be needed to limit fault current because the source itself may not provide much impedance. After the fault is cleared, the voltage angles will depend upon the central control not upon rotor swings. To rebalance load and generation, the central control will therefore need accurate up to date information on the status of the system and the status and capabilities of each energy source and energy storage device. This could also require resolving the network equations quite often, possibly once every few cycles.
- A slower-acting dispatch function could be used to reapportion the power producing device set points to optimize system security, minimize costs, and recognize thermal and energy limitations
- The energy sources might have governors to increase/decrease the power (fuel) when the charge on the DC-shunt capacitor is low/high
- A centralized control might permit a faster response to system disturbances than can be achieved with the traditional, decentralized control. The overall speed of response would still however be limited by the inherent speed of the individual energy sources. Electrical frequency excursions and phase unbalance are not problems with this control architecture because the frequency and phase relationships are fixed. A micro-grid based upon this architecture should be able to disconnect from the AC system seamlessly if it is not exchanging too much active and reactive power before disconnecting. Reconnecting with the utility system might be easy to automate with this type of control since the voltages should already be synchronized.
- In a dispersed system, centralized control would require fast and secure computing, communications, and system monitoring. This requirement introduces additional modes of failure that will decrease the reliability of the system. This architecture would not take advantage of much of the present technology.

An AC Micro-Grid With Current-Controlled Converters and an Optional Centralized Controller

This control system design might have the following attributes:

- Most of the electrical sources in the micro-grid would be static converters generating a fixed amount of active current, which is in phase with voltage. These converters might also be designed to generate some reactive current, which is out of phase with voltage. In some cases they might be directly connected to the grid without a step-up transformer.
- At least one source or an energy-storing device would be used to define the three-phase, AC voltage magnitude, phase position, and frequency and to supply enough active current to balance the system load and generation. If this source is bridge connected, its frequency and phase angle might be referenced to the local utility as described in the previous section. Its

prime mover output might then be governed to control the voltage on the DC side of the bridge. If this source is not bridge connected, it will need a governor to control frequency by adjusting the prime mover output.

- A central control may monitor the grid, load, and sources and specify the active current level for the converters that are acting as current sources and that also have controllable energy sources. In doing this, the controller will need to consider the capabilities of each controllable energy source. The controllable energy sources will be programmed to directly or indirectly follow the changes in the AC power output from their converters.
- Changes in system load would initially be picked up by the voltage-controlling source but the centralized control might quickly respond to reapportion some or all of the load change to other sources.
- This type of micro-grid can probably be implemented to some degree with existing devices. Most of the bridge connected energy sources are current controlled. For small systems, it may be the cheapest to implement because step-up transformers may not be needed for the sources.
- Loss of the voltage-controlling converters will at least temporarily shut down a micro-grid based upon this architecture. A micro-grid based upon this architecture would therefore probably be inherently less reliable then the present U.S. utility network. The voltage-controlling source and connecting grid will need to be sized to instantly pick up load changes at least until the central controller can reapportion load and other energy sources can respond. Also applying current sources for voltage regulation in distribution system may be tricky (see "Voltage Magnitude Control in Micro Grids") and it may be difficult to coordinate protective devices in a system with mostly current sources.

A DC Micro-Grid

DC micro-grid control might be structured much like a multi-terminal, high-voltage, direct current (HVDC) system. It may have the following attributes, but other architectures are also possible:

- The energy sources and loads would probably be connected to the DC micro-grid through bridge converters. Energy sources that function as DC current sources might be directly connected to the micro-grid. The sources and loads would be connected in parallel on the DC side.
- All but one of the converters would be controlled to maintain a specified direct current or power the remaining converter would normally be controlled to hold the desired level of DC voltage. During steady state operation, its current will therefore equal the sum of the currents in all of the other converters. This controller will also have a current limit that is set at a lower level so it will not normally be active.
- If one of the current-control converters cannot maintain the specified level of direct current, the voltage-control converter will automatically pick up the difference until it reaches its current limit, which is normally approximately 10 percent lower. The DC voltage will then automatically drop to the level that the converter previously controlling current can maintain.

- A central control monitors the status of the converters and specifies compatible current set points for each.
- A DC micro-grid would have several advantages over an AC system:
  - The transmission losses are lower if the same amount of power is transmitted at the same peak voltage
  - Two wires or cables will carry almost as much power as three wires do in an AC system
  - The voltage drop across the transmission system will be less
  - Energy sources that function as DC current sources might not need converters to connect them to the grid
- It will also have several disadvantages. Some of the most important are:
  - It is not convenient to transform voltage so power can be transmitted at higher voltages
  - Alternating current energy sources and loads would require converters to connect them to the grid
  - Coordinated control and operation of multiple converters can be challenging
  - It is not easy to sectionalize high-voltage, DC networks to remove only the faulted elements during a disturbance. This can be done with low-voltage networks more easily
  - AC breakers interrupt the current when the sinusoidal current is zero. Current interruption is difficult in DC systems at high voltage levels because there are not naturally occurring current zeros at which current can be terminated. High voltage transients will result if current flowing through an inductive circuit is abruptly interrupted. Direct current breakers that artificially force the current to zero before opening the circuit are feasible but are not presently commercially available at high voltage levels and would be more costly than AC breakers. Such breakers and interrupting devices are available at lower voltage levels and so lower-voltage, DC micro-grids of approximately 1000 volts or less may make more sense technically than high-voltage, DC micro-grids.

DC, Flow-Blocking Device

DC, micro-grid architectures based upon DC-voltage sources are also possible. This architecture might not require a centralized control to balance current set points. It would therefore be easier to accommodate changes in load and generation. It would, however, be necessary to interrupt high direct currents when system faults occur. One interesting aspect of the low-voltage, DC micro-grid that has already been discussed earlier in Chapter 2 is the fact that diodes or other semiconductor devices could be used to control the flow of fault currents, steer generation contributions, and rapidly reconfigure the grid. An example of a silicon controlled rectifier (SCR) –based device is shown in Figure 3-7. The device can be triggered to allow one-way current flow in either direction (depending on which SCR is gated on) and also can block flow (if both are gated off) or allow bi-directional flow when both are gated on. This device would allow considerable flexibility in the control and protection of DC micro-grids. The surge arresters employed in Figure 3-7 are to protect against surge voltages that would be generated during interruption of DC currents with the device—these switching surges would also need to be controlled on the system so as not to damage loads and equipment. Figure 3-8 shows how the flow-blocking device can be applied to control the flow of generator contributions to loads and limit the exposure of some generators to fault conditions. Because the SCR-based device can be instantly (within milliseconds) reconfigured, the contributions can be blocked, redirected, or started as needed to facilitate operation of the micro-grid. The device can be employed to improve power quality on DC micro-grids and mitigate the propagation of voltage sags.

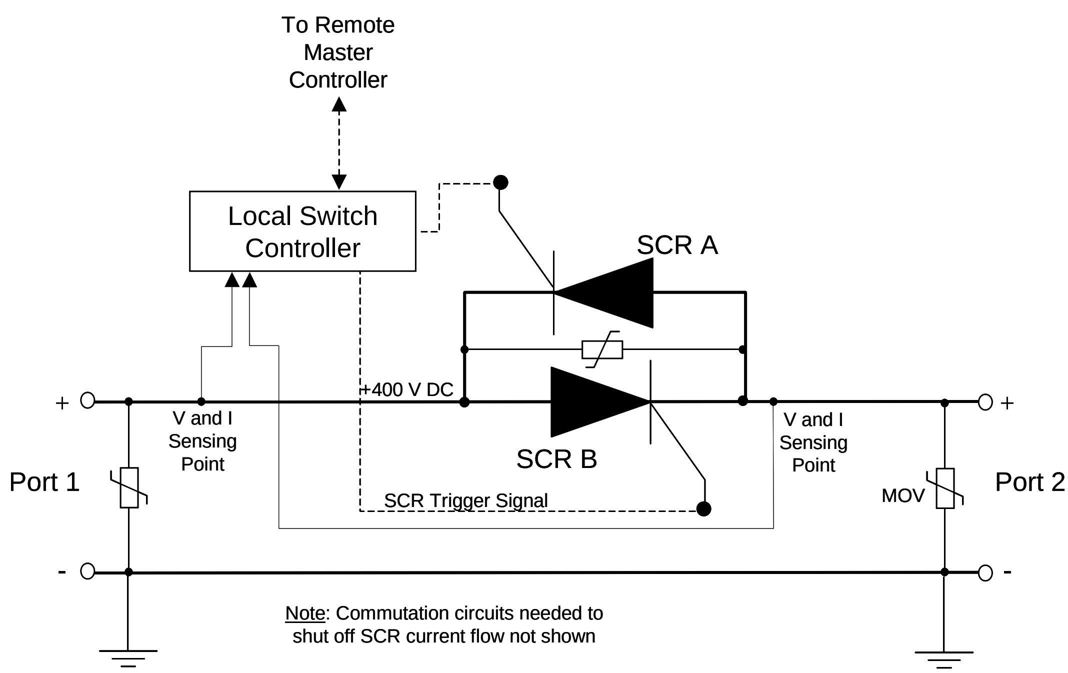

Figure 3-7
SCR-Based, DC, Micro-Grid, Flow-Blocking, and Sectionalizing Device

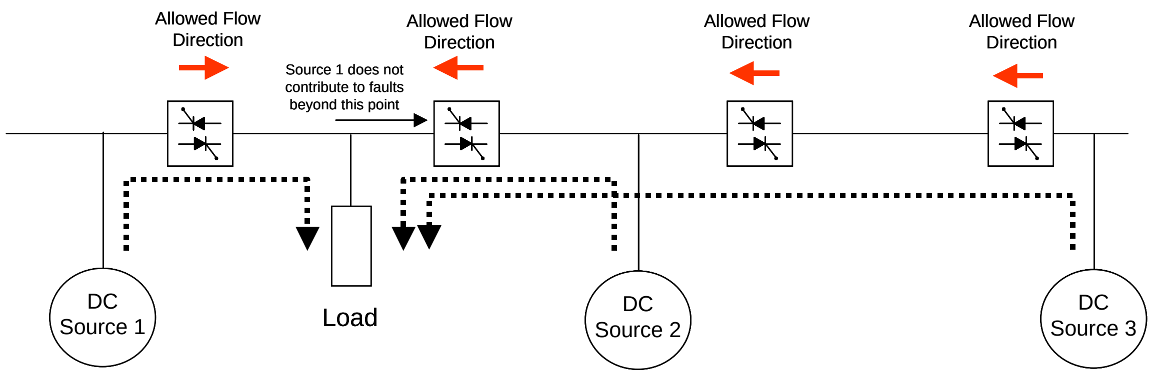

Figure 3-8
Application of SCR-Based, Flow-Blocking Switch

4

COMPARISON OF MICROGRIDS WITH TRADITIONAL POWER SYSTEM APPROACHES

Introduction

Current interest in micro-grids is predicated on the basis that they offer significant benefits compared to traditional power system designs, which are based on central-station plants and the interconnected T&D infrastructure required for delivery of power. This chapter takes a look at the potential benefits and drawbacks of micro-grids in an effort to determine the value of micro-grid approaches with respect to conventional T&D system approaches.

In making this comparison, some key areas that are clearly important include:

- Cost
- Efficiency
- Reliability
- Potential for ancillary services

Costs of Integrated Micro-Grid Systems Compared to Traditional T&D Systems

In comparing the cost of micro-grid systems to conventional T&D systems, it is important to analyze the components that make up the cost of energy delivered via the traditional bulk power system and compare those to the costs of energy delivered via micro-grids. The cost elements of the traditional power system include the bulk generation, transmission, sub-transmission, distribution substation, primary feeder, and secondary system. For a micro-grid, the cost is the distributed generation cost (including all factors associated with this) added to the cost of the power system that makes up the micro-grid. If it is a low-voltage micro-grid, the only cost is basically that of the low- voltage wiring infrastructure with all of its controls and protection—there is no high-voltage infrastructure. Figure 4-1 is an example showing a hypothetical comparison between a utility with a delivered energy cost of 10.5 cents per kWh (slightly above the national average) and a micro-grid at 10 cents per kWh. Note that the cost of micro-grid generation assumes the recovery of waste heat; without this, it would be a few cents more expensive in this example.

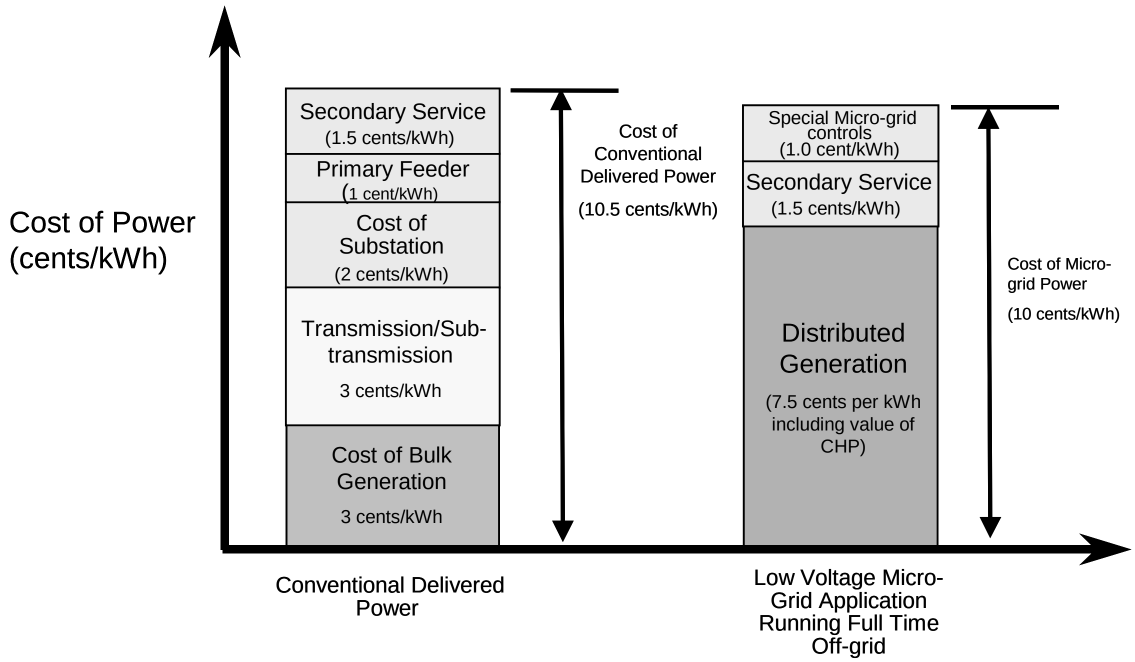

Figure 4-1
Hypothetical Comparison between the Costs of Conventionally Delivered Power and Costs of a Low-Voltage Micro-Grid Application

The example of Figure 4-1 intentionally contrasts a full-time micro-grid to conventionally delivered power. If we had attempted to contrast a part-time micro-grid (one that runs in parallel with the utility system some of the time), then some of the T&D costs would need to be assigned to the micro-grid costs, and the analysis becomes much more complex. Also note that the cost structure of each utility company varies, so the breakdown of costs given in Figure 4-1 for conventional power are meant to be for illustration purposes only.

In our example of Figure 4-1, we used about 10 cents per kilowatt-hour for the cost of energy produced by the DG, and then we discounted that by another 2.5 cents/kWh to account for the value of the heat-recovery option. Therefore, the net cost of electricity production was 7.5 cent/kWh from the DG. This is a fairly reasonable assumption for a good CHP application with an internal combustion engine and with typical fuel prices. DG can be much more expensive than this if an emerging technology is employed, fuel costs are higher than average, or the machines are underutilized. For applications that do not have heat recovery and with some of the emerging technologies that are more expensive, costs can easily be higher than 15 cents per kilowatt-hour.

Table 4-1 summarizes current costs and expected future costs for some of the various DG technologies that are available. The costs shown include the range of expected fuel prices and capital cost variations based on the scale of the DG plant. There are economies of scale for the DG technologies, so larger units tend to have lower costs per kilowatt of capacity installed and the smaller ones the higher cost. The capital costs shown in Table 4-1 represent the bare-bones minimal installed costs for DG equipment from the largest size to the smallest size. If additional equipment or effort is needed for the project such as special switchgear, interface transformers, interconnection studies, fuel compressors, heat recovery units, or utility system modifications, they may add a considerable amount to the total system installed cost. This table represents only the DG cost and not the cost of any micro-grid distribution equipment.

Table 4-1
The Cost of Distributed Generation Is Currently the Major Cost Contributor in Micro-Grid Systems

Generation Technology	Present Cost (2001)		Predicted Future Cost in Year 2010		Cogeneration Potential
	Capital Cost Range ($/kW)	Cost of Power (cents/kW)	Capital Cost Range ($/kW)	Cost of Power (cents/kW)	
Internal Combustion Engine (ICE)	300-900	7-15	300-700	4-10	Yes
Conventional Combustion Turbine (CT) 1-10 MW size range	500-1000	5-15	400-700	4-10	Yes
Microturbine (<500 kW)	700-1000	9-15	350-700	7-10	Yes
Photovoltaic	5000-8000	20-40	2000-3000	10-20	No
Wind Turbine	700-1200	4-20	500-1000	3-15	No
Fuel Cell	4000-50000	15 or more	350-1500	5-10	Yes

Given the costs of the distributed generation options, it is clear that many DG applications will not really be lower in cost than the lowest-cost utilities in the country. The lowest-cost retail utility power tends to be in the range of about 5 cents per kilowatt-hour, whereas the lowest cost DG cannot quite get this low even with heat recovery. The highest-cost conventional utility power is higher than 20 cents per kilowatt-hour in some island areas such as Hawaii, and DG is much more competitive in regions with high utility prices as long as fuel costs for the DG are still reasonable in those areas. Often, there is a tendency for areas with high utility electricity prices to also have high fuel prices, which tends to limit the competitiveness of DG solutions. The best areas in the country for DG are those that have high conventional power costs but low fuel costs. The average cost in the U.S. for conventional utility electricity is in the range of 8 to 9 cents per kilowatt-hour. If the DG cost plus the micro-grid infrastructure cost is lower than the utility cost, then a micro-grid makes sense on a pure cost perspective.

Figure 4-2 is an illustration of the cost distribution for conventional utility power overlaid on the cost distribution for distributed generation options. What is clear is that most DG scenarios are currently more expensive than most conventional utility situations. However, there are some applications where DG is lower in cost. Combined heat and power in regions with low fuel costs and high conventional power costs are the most likely candidates to make sense. DG may also be applied even when it costs more, simply because it improves reliability.

The costs shown in Table 4-1 are the distributed generation costs only and do not include the costs of the non-generation micro-grid infrastructure. The cost of the non-generation micro-grid infrastructure will vary widely due to the wide range of architectures that are possible. Some micro-grids are basic low-voltage systems, and others are networked high-voltage primary systems aimed at premium power markets. The cost added to generation will likely be in the range 2 cents per kilowatt-hour for the most basic low-voltage micro-grids to 10 cents per kilowatt-hour for very sophisticated networked primary micro-grids that have a variety of power-conditioning and power quality enhancement equipment. Certainly, the basic low-voltage system with no frills can be competitive in a number of scenarios with utility power. However, even the premium power micro-grid is competitive if its cost is compared to a premium power conventional distribution system or compared with the installation of numerous local UPS equipment at each load.

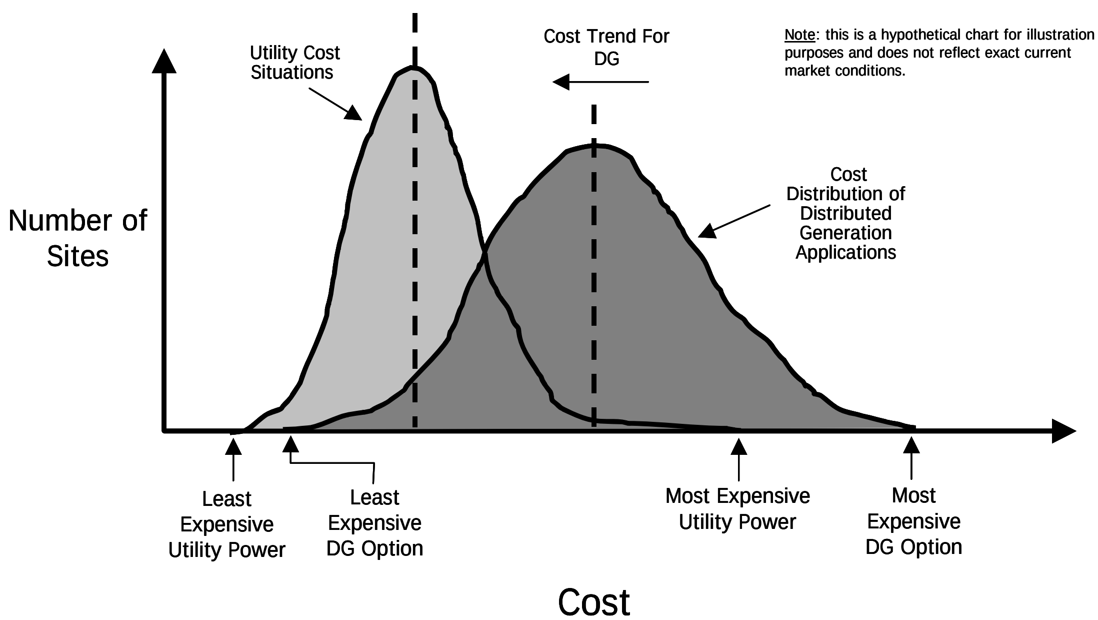

Figure 4-2
Illustration of Cost Distribution of Utility Energy Cost Scenarios Overlaid on Possible DG Cost Scenarios

Another cost factor to consider is that the electricity costs of Table 4-1 are based on ideal operating conditions for the distributed generators. If the DG is operated at light load, this will reduce the efficiency and increase the capitol investment per generated kilowatt-hour. Therefore, the cost of energy goes up. Generation plants have the lowest cost of production generally when they are operated at full load (at the highest possible capacity factor).

Micro-Grid in Lieu of a Line Extension

There are applications for fulltime micro-grids that stand-alone from the T&D system and can make economic sense even when the cost is very high. One such application is the line extension deferment. Because the cost of building new primary distribution systems is in the range of $40,000 to 100,000 per mile (depending on the line design, terrain, and local labor costs), extending a line to serve a small load such as village or cluster of vacation homes can be more costly than building a micro-grid.

As an example, a micro-grid to serve 10 clustered vacation homes using a low-voltage configuration and ICE units could be completed for less than $100,000. If the cluster of homes were located 3 miles from the nearest conventional distribution feeder, it probably would make more sense to build the micro-grid than to extend the distribution line—that is, assuming fuel can be delivered to the site and the ICE units and micro-grid can be operated with sufficient reliability to keep the customers happy.

Efficiency of Micro-Grid Systems

There are two sides to the distributed generation and micro-grid efficiency argument. One school of thought considers that distributed generation is extremely efficient compared to the bulk utility system, and the other school considers that it is less efficient than a current central-station power plant. To determine which argument is correct, let's consider both arguments.

The Case for Micro-Grid Efficiency

If you were building a micro-grid today, you could choose from a variety of off-the-shelf distributed generation technologies that have peak electrical efficiencies ranging from about 25% up to more than 42% efficiency. These would include combustion turbine units, internal combustion engine (ICE) technologies, and microturbines. There are also commercial phosphoric acid fuel cells available that are about 38 to 40% efficient. The efficiency of all these distributed generation products are not particularly high compared with new central-station combined-cycle power plants that can be up to 55 to 60% efficient. However, if heat recovery from the distributed generators is performed and if it is used effectively, then the total energy efficiency of the process can be as great as about 90% in a very-well designed CHP application.

This level of efficiency far exceeds that of a central-station plant that does not have heat recovery. Furthermore, the central station plant will lose some additional power in the transmission and distribution process (about 8 to 10% on average). Therefore, for a new combined cycle plant, the net efficiency (power delivered to load) is perhaps about 50 to 55% in the best case. Most DG applications with properly designed heat recovery have better than 50 to 55% efficiency. Some people also consider that the "fleet" average of utility power plants, which include many older steam-fired plants and simple cycle plants, is more on the order of 35 to 40%. When T&D losses are factored in, only about 1/3rd of the energy in the utility company fuel input actually reaches the load as electricity. On the other hand, with distributed generation in a combined heat and power configuration, up to 90% of the energy in the fuel is usually utilized.

Even more promising is the fact that existing DG technologies are steadily improving in their electrical efficiency, and new emerging products will soon be available. For example, conventional DG-scale combustion turbine and reciprocating engine products are expected to approach about 50% efficiency by the end of this decade due to improvements in designs and materials. In the next 5 to 10 years, high-temperature fuel-cell technologies such as the solid oxide and molten carbonate fuel cells are expected to be fully commercialized and should have electrical efficiencies from 55 to 60%. Manufacturers of fuel cells are also working to develop fuel-cell/combustion turbine hybrid systems, where the electrical efficiencies may reach 70% or better.

With electrical efficiency levels this good coming in the near future, it would seem that the case for the efficiency of distributed generation and micro-grids compared with conventional power systems is quite strong and getting stronger. However, let’s now look at the case against the efficiency of distributed generation.

The Case against the Efficiency of Micro-Grids

Many power system engineers rightfully argue that DG efficiency may often be less than the bulk power system efficiency. First of all, if the distributed generation application does not employ heat recovery, then its peak efficiency will be about equivalent to the utility central-station “fleet” average efficiencies or even a bit lower for many of the current technologies. This does not sound too bad until one recognizes that comparisons to the “fleet” average is not a very meaningful comparison because the argument for micro-grids and DG is always a comparison of investing in new central plants versus investing in micro-grids and DG. It is not a fair comparison to compare existing fleet plants to the latest state-of-the-art DG.

Another flaw in the argument is that the efficiencies cited for distributed generators are often peak efficiencies that occur at only the optimal loading point (near rated load). In many micro-grid applications, it will not always be possible to keep all generators loaded at their peak efficiency point because the load factors on the micro-grid are much less than 1 and because it is always necessary for some of the generation to be load following and oversized slightly to handle load steps and so on. As a result, the efficiencies obtained in practical operating conditions can be many percentage points lower than the stated peak DG efficiency (such as 25% instead of 30%). Ancillary equipment such as gas compressors and other devices can cut back a few more percent on the overall system efficiency. Finally, even when CHP is used, if the heat is poorly recovered or cannot be fully utilized because of a mismatch between heat demand and electrical production, then CHP efficiency may actually not add that much to the overall efficiency. Looking at this total argument, it is clear that poorly designed micro-grid applications could actually have lower total efficiency than installing new central station plants.

Efficiency Conclusions

The efficiency of distributed generation can certainly be greater than the bulk power system, but it is important to recognize that this is not universally guaranteed for all applications, many applications are less efficient when they do not employ the correct elements needed for efficiency success! Micro-grid distributed generator applications that are *sure* to outperform combined-cycle central-station options by a wide margin are those that satisfy both of the following:

- They are operated at very high capacity factors that will ensure that they are near the most efficient operating state most of the time
- They employ heat recovery whereby most of the recovered heat can be used for useful purposes (see Figure 4-3)

If the above two conditions are not satisfied, then the DG application may not be as efficient as a central-station combined-cycle application and it will need to be studied closely to see if there is an advantage in this category.

Distributed generation applications that meet the following two conditions will likely be less efficient than even the utility "fleet" average:

- DG applications that do not have heat recovery
- DG applications with generators that have less than 35% peak-rated efficiency and are operated at less than 50% capacity factor

Figure 4-3
Combined Heat and Power Applications for DG Are the Best Route to High Efficiency

Reliability of Micro-Grid Compared to Conventional Power

The reliability of average power distribution circuits in the United States is about 99.98%, which means that power is available for 99.98% of the year or there are about 2 hours of cumulative interruption time each year. This is far better than typical individual distributed generators such as ICE units or CT units, which have availability in the range of 95 to 98%, depending on how they are maintained and operated. To achieve 99.98% with ICE units requires more than one unit, and they need to be sized so that if one should fail, the others can pick up the load.

As an example, if a micro-grid has a load of 1 MW and two 1 MW ICE generators are employed to support the island, then this is an N-1 design contingency—meaning that if one unit fails, then we can still carry the micro-grid load (see Figure 4-4). If each generator in our example has a reliability of 97%, then two in parallel (assuming their failures are independent) have a reliability of 99.91%. This is much better than one generator but still several times worse than the average conventional power distribution feeder. If fulltime micro-grids are to have reasonable reliability, then they must be designed for the N-1 contingency or even N-2. Using the utility system as a backup source is one possibility that avoids the need for redundant generation capacity, but from a cost perspective, there may be standby charges that are assessed to the DG operator that seriously impact the system economics.

If redundant generation is used, then usually units are broken down into clusters of 3 to 5 units as opposed to the 2 units in our example because this allows less overcapacity (see chapter 2 on reliability for more details). The important point here is that the reliability of a DG in a stand-alone micro-grid can be increased to that of a typical distribution system if an N-1 or N-2 design is employed given the typical availability of DG products. This design redundancy does come with cost and performance penalties because there is always some underutilized generation capacity.

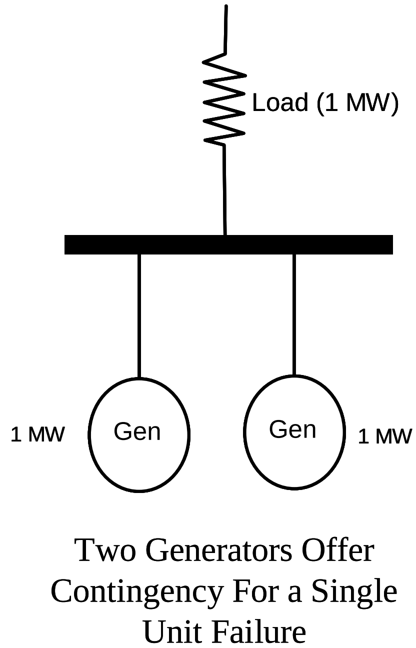

Figure 4-4
Two Generators Each Rated to Carry the Entire Load Provide Much Greater Reliability Than a Single Unit

Micro-grids, because they are not connected to the bulk supply and/or because they can quickly isolate themselves from the bulk supply, will have less effective exposure to bulk system disturbances. The fulltime low-voltage micro-grid may be one of the best performers of all in this regard. It will have fewer interruptions of a fault-related nature because it has little exposure to the types of fault conditions that commonly afflict the high-voltage distribution, sub-transmission, and transmission systems. Thus, while generation reliability is an issue for micro-grids, they do have the advantages of fewer faults and voltage sags due to their limited exposure.

Potential for Ancillary Services

Micro-grids offer the potential for two key ancillary services that may be able to generate a revenue stream for the owners/operators of the micro-grid. The two key ancillary services are:

- Thermal energy
- Reliability

These services really cannot be offered with a conventional power system because generation is located a long-distance from loads and because it is very difficult to have targeted high-power quality/reliability on the conventional system. So these are service areas where the micro-grid with distributed generation really has an advantage over a conventional power system. Let’s first consider the benefit of heat production and sale as a product. If the micro-grid is established at a single customer site, business park or even full-feeder-level area, heat can be recovered from the generation systems and distributed throughout the area for various purposes. Some basic services that can be provided with heat include:

- Space heating
- Potable water heating
- Air-conditioning (via chiller systems)
- Refrigeration (via chiller systems)
- Process heat for a manufacturing, food industry, or agricultural process

To understand the value of waste heat from the generation process, let's consider how much heat is produced each time a kilowatt-hour of electricity is created. First consider that natural gas costs in the range $4 GJ (note 1 GJ = 278 kWh). This is equivalent to about 1.4 cents per kWh. If generation is 40% efficient, then for each kilowatt-hour of electricity produced, 1.67 kWh of heat is produced. Thus the value of heat is about 1.4 cents x 1.67 or about 2.33 cents per kilowatt-hour of electricity produced. Of course not all of this can be recovered or used, but if 85% could be recovered and used, then at current gas prices this thermal energy offsets the need to burn about 2 cents of natural gas for each kilowatt-hour of electricity produced. The heat could be sold to customers as an added service that would generate revenue for the operator of the micro-grid.

Reliability is another service that could be sold. Customers might be willing to pay some fraction of the cost they would otherwise spend on UPS equipment to mitigate their power quality/reliability problems if they were located on a conventional system. Revenue obtainable from such "reliability service" could be estimated by considering the annual carrying cost of UPS equipment that the micro-grid customer has deferred, then charging a fee that is less than that so that both the customer is happy and the micro-grid operator gets some revenue. This is just a concept, and it is not clear, given that most customers will not pay electric providers for reliability, that this could actually be achieved in practice. Perhaps another solution is simply to charge a premium for the energy that any customer located on the micro-grid uses because the micro-grid could be marketed as a premium power park with above average power quality and reliability. A premium electric rate that did not exceed the avoided carrying charge on the deferred UPS equipment could be reasonable. This could amount to perhaps 1 to 2 cents of additional charge per kilowatt-hour for some customers.

5
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the history of micro-grids in the early twentieth century and society's movement to a centralized power system by mid-twentieth century, it is ironic that 100 years later, we have come full circle and are once again thinking of micro-grids as potentially viable power-system architectures for the 21st century. Improvements in distributed generation technology, the increasingly demanding power quality/reliability needs of loads, and public policy that is encouraging distributed generation may have begun to shift the balance of power back in favor of micro-grids. If this shift continues, it is possible that the widespread re-introduction of micro-grid systems may occur within the next decade or so. Of course these new micro-grids will not be your great grandfather's micro-grid. They will employ the very latest clean-generation technologies—such as fuel cells, photovoltaics, and microturbines—and will have advanced control systems and power-conditioning features that make them much more efficient and reliable than the original micro-grids. Moreover, they will be fully compatible with the demanding digital loads of the 21st century.

There are signs that the shift to micro-grids may have begun. There are now numerous examples of DG systems that serve college campuses, hospitals, manufacturing plants, and other institutions that are employed in a basic micro-grid architecture, allowing the generation to operate in parallel with the utility system under normal conditions but transitioning to an islanded state during interruptions in the utility system. These types of installations have performed for many decades at commercial and industrial facilities. In recent years, they have become increasingly sophisticated and more numerous as the technology of DG and microprocessor-based energy-management controllers have improved. Of course, these existing installations are still fairly basic compared to some of the business park arrangements and networked adaptable micro-grids discussed in this report. These more evolved architectures, it is hoped, can be the next generation of micro-grids and further advance the economics and performance of micro-grids to truly make them mainstream power-system architectures.

Although there is much promise for micro-grids, it is not yet clear whether micro-grids can emerge again as anything other than a niche application or if they will become a significant part of the power-system infrastructure. Certainly, micro-grids can offer significant benefits in terms of improved reliability, support for transmission and distribution (T&D), greater efficiency through combined heat and power (CHP), and power-system designs that potentially cost less. But shifting to micro-grid-intensive power-system architecture will require a significant rethinking of the design of the distribution system, as well as layout, protection, and control approaches used in the industry. Furthermore, there are technical and cost-related issues that still need to be resolved for the widespread use of micro-grids to be realized.

For example, the DG technologies that are most promising for use in residential/commercial micro-grids, such as fuel cells and renewable energy sources, are still too expensive for truly economical application in micro-grids compared to conventional T&D systems. On a cost-of-energy basis, even low-cost DG technologies such as the internal combustion engine and turbine engine are usually competitive only in higher-cost utility power markets and only when CHP can be employed or reliability enhancement is needed. There are reliability and maintenance issues associated with the emerging DG technologies that are still in the early commercialization phase, and many control issues for integrated micro-grid systems have yet to be worked out, although many of the techniques could hopefully be adopted from the bulk power system. New equipment to resolve these issues also needs to be developed, and design experience needs to be obtained to establish the complete infrastructure needed to support development of the various types of micro-grid applications.

The regulatory and business questions revolving around the micro-grid also need to be resolved—questions such as:

- Who will own and operate the micro-grid?
- Will wires companies be allowed to operate the micro-grid with its embedded generation?
- Can ancillary services such as waste heat and reliability be sold and, if so, for what price?

These questions need to be answered so that utility companies and others can invest in building micro-grids and recover the monetary benefits of operating those systems.

The electricity customer is another part of the picture that is very important to the ultimate success of the micro-grid. Key questions include:

- How will customers respond to the idea of being located on such a system?
- Will they embrace it, be indifferent, or will they be fearful of the reliability risk of the new technology?

There is a fair amount of marketing development required to identify the response of electricity customers to this alternative electric service and their willingness to pay for any ancillary services or other real and perceived benefits that these services may offer.

Overall, despite all of the issues above, the micro-grid appears to be a viable alternative to traditional designs in a number of possible applications, and the simple single-source micro-grid is already a commercial reality, with considerable successful field experience being obtained. For the future, a number of very promising system configurations were identified, including the low-voltage networked AC micro-grid and low-voltage DC micro-grid. These approaches are quite radical compared to existing power system designs but offer the opportunity to reduce a significant part of the cost of power systems by eliminating much of the need for high-voltage infrastructure in all environments but those with the highest and load densities. Furthermore, they may substantially improve power quality and reliability compared to existing system designs.

Recommendations for Future Investigations

Based upon the preceding discussion, there are a number of future research projects that can support the further development of micro-grids. These include:

1. Interconnection Requirements for Distributed Generation, Micro-Grid-Compatible Distribution-System Architecture, and Control Methodologies

Much ongoing work in the industry aims to develop interconnection standards such as the IEEE P1547 for standard distributed generation that does not necessarily operate as a micro-grid. That work is focused on the requirements for interconnection of DG to standard distribution systems, and much of it does not deal with the issues needed on micro-grid systems. The operation of distributed generation on micro-grid systems, such as architectures with dispersed multiple generation resources, will require significant changes in the controls, relay settings, grounding practices, and other technical interface requirements compared to those used for standard distribution systems. A project is recommended to evaluate and develop approaches for DG control and protection when DG is operated in micro-grids. The project should define the best methods to optimally dispatch generators, recover from system blackouts, control frequency and voltage, and handle electrical disturbances. Many of the recommendation would be based upon dynamic simulations of DG, representing various options for protection, voltage control, and frequency control.

Another key element of this research is to determine the ideal design and layout for a power-distribution system. Designs need to be developed that are compatible with micro-grid operation. These new designs will need to be much more like a transmission system with zone-based relaying and bi-directional capability. Design issues include the feeder configurations, types of protection devices and relaying needed, voltage-regulation equipment, grounding, and other design factors that are required to make micro-grids technically feasible. This part of the project would also include developing guidelines for primary and secondary power-system designs based on computer load-flow simulations that would identify the needed physical lengths of the primary circuits, spacing between generation plants, conductors sizes, and equipment ratings needed to facilitate proper system operation.

2. Laboratory-Scale Model of Micro-Grid

As a verification of the control algorithms and system-design approaches developed in recommended project #1, a model of a micro-grid with the following characteristics would be constructed:

- Scaled-downed, tabletop sized
- Scaled representative loads

- Feeder impedance representation
- Small rotating and static-based power sources
- Simulated communication links that connect with an integrated controller
- Used for studies of steady-state, dynamic, and transient behavior of micro-grids

This experiment with a scaled-down model could be similar to a transient network analyzer (TNA) study and would offer much insight into how to “tune” the controls to achieve optimal micro-grid performance.

3. Proof-of-Concept Designs, Modeling, and Lab Tests for Low-Voltage AC and DC Micro-Grids

Several low-voltage architectures for micro-grids were identified in this report that may be a radical departure from existing distribution systems but which have great promise to lower cost and improve power quality. These include both AC and DC designs. It is recommended that these be investigated with sufficient detail such that detailed designs for both AC and DC systems can be developed, including the required protection, grid layouts, types of loads, and load densities that can be served; spacing between connecting nodes and generators; and voltage-drop calculations.

4. Detailed Economics of Micro-Grids

Detailed case studies are recommended to evaluate the full lifecycle costs of micro-grids compared to conventional power-delivery systems. These studies should quantify the cost of all equipment needed and compare this cost with more traditional solutions. Case studies for several systems are recommended, including a micro-grid in lieu of a line extension, a substation-based micro-grid, a small residential cluster, and a power quality business park.

5. Equipment and Devices Needed for Micro-Grids

There are some physical devices that may be needed for successful micro-grid deployment. For example, chapters 2 and 3 discussed a flow-blocking device that might be helpful at implementing the control and protection that is needed for DC and AC micro-grid designs, and there are many other useful devices that are worth investigating. These include:

- Micro-grid dynamic stabilizer with ultra-capacitor energy storage and other types of power conditioners
- DC and AC flow-blocking and sectionalizing devices
- Wide range DC-to-DC converters
- Static distribution transformers
- Self-synchronizing circuit interrupters and switchgear

- High-voltage DC interrupting devices
- Whole-house inverter systems
- Secure high-speed and low-speed communication technologies such as power-line carrier and wireless-based devices suitable for linking micro-grid equipment
- Inverter control that will enable the DG to actively support the AC system voltage and frequency during electrical disturbances
- CHP and heat-recovery products that can add value to micro-grids

These and other devices could be investigated to determine their availability and/or the possibility for development if no suitable products are available. Studies could range from paper-based design analysis up to the development of prototype devices. Prototypes would be developed from scratch or by modifying existing products where appropriate.