



**CALIFORNIA
ENERGY
COMMISSION**

**Integration of Distributed Energy
Resources**

The CERTS MicroGrid Concept

CONSULTANT REPORT

OCTOBER 2003
P500-03-089F



Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

Prepared By:

CERTS Program Office
Lawrence Berkeley National
Laboratory
20 Cyclotron Road,
MS90-4000
Berkeley, CA 94720

Contract No. 150-99-003

Prepared For:

Don Kondoleon,
Project Manager

Laurie ten-Hope,
PIER Program Area Lead

Terry Surles,
PIER Program Director

Robert L. Therkelsen,
Executive Director

DISCLAIMER

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.



Preface

The U.S. Electricity Grid Today The U.S. electric power system is in the midst of a fundamental transition from a centrally planned and utility-controlled structure to one that will depend on competitive market forces for investment, operations, and reliability management. Electricity system operators are being challenged to maintain the reliability of the grid and support economic transfers of power as the industry's structure changes and market rules evolve. Meanwhile, U.S. economy depends more than ever on reliable and high quality electricity supplies. New technologies are needed to prevent major outages such as those experienced on the Western grid on August 10, 1996, which left 12 million people without electricity for up to eight hours and cost an estimated \$2 billion.

The Consortium for Electric Reliability Technology Solutions (CERTS) was formed in 1999 to research, develop, and disseminate new methods, tools, and technologies to protect and enhance the reliability of the U.S. electric power system and functioning of a competitive electricity market. CERTS is currently conducting research for the U.S. Department of Energy (DOE) Transmission Reliability Program and for the California Energy Commission (CEC) Public Interest Energy Research (PIER) Program. The members of CERTS include the Electric Power Group, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, the National Science Foundation's Power Systems Engineering Research Center, and Sandia National Laboratories.

Consortium for Electric Reliability Technology Solutions

White Paper on

Integration of Distributed Energy Resources

The MicroGrid Concept

Appendices

Prepared for

Transmission Reliability Program
Office of Power Technologies
Assistant Secretary for Energy Efficiency and Renewable Energy
U.S. Department of Energy

Energy Systems Integration Program
Public Interest Energy Research
California Energy Commission

Prepared by

Robert Lasseter, Abbas Akhil, Chris Marnay, John Stevens,
Jeff Dagle, Ross Guttromson, A. Sakis Meliopoulos, Robert Yinger, and Joe Eto

April 2002

The work described in this report was coordinated by the Consortium for Electric Reliability Technology Solutions, and funded by the Assistant Secretary of Energy Efficiency and Renewable Energy, Office of Power Technologies of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and by the California Energy Commission, Public Interest Energy Research Program, under Work for Others Contract No. BG 99-39.

APPENDIX A. MicroGrid Technologies

Many small (less than 250-kW) generation and storage technologies are already being used to shave peak generation and provide back-up generation during power system outages. This appendix gives a brief overview of each of the major technologies currently in use or expected to soon become available. These technologies are divided into two major categories: generation and storage. Generation technologies described are: microturbines, fuel cells, photovoltaic cells, solar thermal arrays, wind turbines, reciprocating engines, and small hydro installations. Storage technologies addressed are: batteries, flywheels, superconducting magnetic energy storage systems, and supercapacitors. All of these distributed generation and storage technologies could be grouped together into MicroGrids.

A. 1 Small (<250-kW) Distributed Generation Technologies

The technologies discussed below all use a fuel or power resource that is converted to standard North American 60-Hz electrical power. For most microturbines, fuel cells, and photovoltaic cells, electrical power is generated as direct current (DC) voltage and converted to alternating current (AC) using an inverter. In other words, unlike in large-scale power systems, an power electronic inverter isolates the small mechanical, chemical, or solid-state generator from the power grid. For solar thermal, wind, reciprocating engine, and small hydro generators, turbine shaft rotation is converted directly to AC power. The difference in conversion for technologies that require an inverter and those that produce AC power directly is important for the design and operation of a MicroGrid made up of distributed generation resources.

Microturbines

Microturbines are composed of a generator and small gas turbine mounted on a single shaft. The turbine technology is based on a refinement of automotive turbo chargers and military engines. Microturbines rotate at high speeds, some at nearly 100,000 rpm. A permanent magnet generator spinning at this high shaft speed produces the power in the form of high-frequency AC, which is converted to DC and then to standard 60-Hz AC using an inverter. Most microturbines are fueled by natural gas but can also use liquid fuels such as diesel or jet fuel. These units currently range in size from 30 to about 100 kW; larger units are under development. Most microturbines also have a recuperator to recycle some exhaust heat back to the combustor. A microturbine with recuperator typically has 20-30 percent efficiency. Utilization of waste heat can increase overall system efficiency (electricity and heat) to 70- 80 percent. Because the combustion process is closely controlled and relies on relatively clean burning fuels, microturbines typically produce few emissions.

Microturbines are just now coming to market; one major U.S. supplier is producing units for installation, and several other manufacturers are performing final testing of units that are expected to come to be available on the market in the near future. Many microturbines can operate as stand-alone resources or in parallel with the electrical grid. When operating parallel to the grid, they generally produce fixed power output or function in peak-shaving mode. In the stand-alone mode, microturbines must regulate voltage and frequency and follow load changes. Rapid load following is accomplished using an on-board battery or fast-response fuel control.

Because microturbines do not produce significant emissions, they are expected to be widely applicable in areas with strict pollution controls. With the use of combined heat and power (CHP), microturbines could generate on-site power at costs competitive with those for current purchased power. The limitations of microturbines are noise and emissions. Although these impacts are relatively small, microturbines are located near the point of energy use, so they will likely have greater effect on local residents than the noise and emissions produced by modern central power stations, which are usually located far from population centers.

Fuel Cells

A number of fuel cell technologies are either under development or currently being used to generate power. The attraction of fuel cells is their potential for highly efficient conversion to electrical power (35 to 55 percent without heat recovery). The only technology in general use today is the phosphoric acid fuel cell, which is available in the 200-kW size range. This fuel cell operates at about 40 percent conversion efficiency. Because this device operates at 400 degrees F, waste heat is available as steam, which boosts the overall fuel conversion efficiency. A number of other fuel cell technologies are being developed. For the power industry, these include: proton exchange membrane (low-temperature, hydrogen fueled), molten carbonate (high- temperature), and solid oxide (high-temperature).

All fuel cell technologies operate in a similar manner electrically although they differ in operating temperature, charge carrier (H^+ , O^{2-} , CO_3^{2-} , or OH^-), electrode, electrolyte, catalyst, and current collector/flow field materials. Introduction of a fuel (generally hydrogen) to the fuel cell stack where catalyst material is impregnated in the electrodes and an ion-conducting electrolyte is present causes the separation of ions and electrons and results in electron movement. This movement generates a DC voltage on the stack terminals that is proportional to the number of cells in the stack. The DC voltage is sent to an inverter where it is converted to 60-Hz power. The fuel cell appears to the electricity grid as an inverter, similar to a microturbine.

The ability of a fuel cell to change load levels is dictated by its ability to produce more voltage through consumption of additional fuel. Because most fuel cell stacks are designed to use hydrogen, fuels that are readily obtainable (e.g. natural gas, gasoline, diesel fuel) need to be “reformed” into free hydrogen for use by the fuel cell stack. Reforming can take place outside the fuel cell (for low-temperature technologies) or inside the fuel cell (for high-temperature technologies). The emissions of the fuel cell stack itself are generally limited to water vapor, exhaust air that is depleted of oxygen, and, for direct- -hydrocarbon and direct-carbon fuel cell systems, carbon dioxide. Reforming processes add low levels of nitrogen oxides, carbon monoxide, and hydrocarbons, depending on the specific technology and fuel used.

Although most fuel cell technologies are not yet commercial, they show great promise for use in MicroGrids because they combine high efficiency, high reliability, and quiet operation. Their biggest drawback is high cost.

Photovoltaic Cells

Photovoltaic (PV) devices have been in existence for many years since their early use in the U.S. space program. They rely on sunlight to produce DC voltage at cell terminals. The amounts of voltage and current that PV cells can produce depend on the intensity of sunlight and the design of the cell. PV systems use cell arrays that are either fixed or track the sun to capture additional energy. Because solar energy is a diffuse resource, it takes a large area of PV cells to produce significant power. At a typical cell conversion efficiency of 10 percent, about 10 m² of panels are needed to provide a peak power of 1 kW. To reduce the number of costly PV devices used, mirrors or lenses can be used to concentrate sunlight on to the cells. This increases the PV cell output but requires tracking devices to insure that the array is aligned with the sun.

Photovoltaics, like microturbines and fuel cells, generate DC voltage that must pass through an inverter to produce 60-Hz alternating current for distribution on the utility grid. A PV system's capability to track load changes is limited by available sunlight. Storage is required for stand-alone systems if power requirements exceed available sunlight.

While the sun shines, PV systems operate highly reliably, quietly, and with no emissions. Their largest drawbacks are their high initial cost, the intermittent nature of the solar resource, and the large collection areas they require.

Solar Thermal

Although there are a number of large-scale (several-megawatt) generation technologies in the solar thermal field, the main technology for small-scale generation is the sterling dish. This technology is being tested in the 10- to 25-kW range. In this system, light is concentrated on a small receiver by a sun-tracking array of mirrors. The heat collected by the receiver is transferred to the hot end of a sterling engine. The sterling engine uses working fluid in a closed cycle to push pistons and generate shaft rotation. In a sterling dish, shaft rotation is used to spin an induction generator that is connected to the electric grid.

Like PV systems, sterling dishes have a power output that is fixed by the amount of solar input. In a closed system, storage is required to handle power requirements in excess of the solar energy available at any given time. Because sterling dishes use induction generators, these systems are not easily adaptable to stand-alone operation in a MicroGrid. In the near term, the cost of this technology will remain high.

Wind

Wind generation has been commercially available for many years. The main push has been in large wind farms where wind turbines from 700 kW to 1.5 MW are available and in use. Several smaller wind turbines (<250 kW) are available for use in MicroGrids. These machines typically use an induction generator driven by a rotor with blades. As is true for the solar options, the wind generators' power output is determined by the availability of their energy source. When the turbine is operating in stand-alone mode, any power requirement in excess of the wind energy available must be supplied by storage systems or other generation. Because they

commonly use induction generators, small wind systems are not easily adapted to MicroGrid operation unless other sources supply voltage and frequency control.

Small Reciprocating Engines

Reciprocating engines that run on various fuels are available in small sizes and up to several megawatts. Currently available engines are typically intended for stand-alone or back-up use. These engines, especially the larger ones, have good efficiencies (30 to 40 percent). They operate in stand-alone applications like scaled-down generation plants with synchronous generators capable of controlling voltage and frequency. Waste heat from these units can help boost overall system efficiencies.

Reciprocating engine generators are a mature, low-cost, familiar technology with some attractive benefits for MicroGrids. Their main disadvantages are noise, maintenance costs, and emissions. Emissions depend heavily on the fuel used. Clean-burning fuels, such as natural gas, could result in acceptable emissions profiles, especially if control technologies were used. However, the most common fuel currently in use by far is diesel, which causes serious emissions problems and would preclude the regular use of this technology.

A. 2 Storage Technologies

Storage is important in the MicroGrid both because peak loads are expensive to serve with purchased power and because MicroGrid generation sources may not be able to respond to load changes as needed. Load changes are usually caused by short-lived events, such as fast transients resulting from starting of motors or turning on/off of equipment, or from slower changes that exceed the ramping capability of generation available at any given time.

All the storage systems mentioned in the sections below require power electronics to convert the stored power to standard, 60-Hz, AC, utility-grade power. These systems can be designed to switch into operation in subcycle time frames, so they are ideal for tracking fast load changes or immediately providing back-up if utility power is lost.

Batteries

Batteries are the traditional method of storing electrical energy; there is considerable operational experience with battery systems. Lead-acid batteries, available in almost any size, are used in many applications that require back-up power. Batteries using other chemistries are now also available commercially. Recent improvements have increased energy storage density and extended battery lifetimes. Discharge rates are determined by the battery's design and the chemical reactions used for energy storage.

Batteries store energy in chemical form and are charged/discharged with DC current. This DC current is converted to standard, 60-Hz, AC electrical power by means of power electronics. Most commercial uninterruptible power supplies rely on batteries.

Flywheels

Many improvements have been made to flywheel systems in recent years. These systems now incorporate composite rotors, magnetic bearings, and advanced power electronics. Flywheels store energy in high-speed (up to 100,000-rpm) rotating wheel-like rotors or disks connected to motor/generators. High-speed rotation is important because the amount of power stored in the flywheel is proportional to the square of the rotational speed. The flywheel is “charged” by taking utility power and converting it to drive the flywheel motor, which increases flywheel speed. During a “discharge,” power is drawn from the flywheel by the generator, which slows the rotor speed. Because the output of the flywheel generator is variable, an inverter is used to convert power to standard, 60-Hz AC power.

Flywheel systems come in a wide range of sizes with differing discharge rates for different amounts of time. The flywheel stores a fixed amount of energy (kWh). It can be discharged at high power (kW) for a short time or at a slower rate for a longer period. Flywheels contain no hazardous materials and are not affected by temperature extremes as batteries are, but flywheels are costly and cannot store energy indefinitely.

Superconducting Magnetic Energy Storage

Superconductors allow the passage of electrical current without losses. Electrical energy is stored as a circulating current in a superconducting coil of wire. This circulating current establishes a magnetic field in which the energy is stored. The major energy loss in this system results from the need to cool the coil to very low temperatures. Power electronic interfaces charge and discharge the superconducting coil. Most commercial systems are somewhat larger than 250 kW in capacity. Superconductor storage technology could be adapted to larger MicroGrid applications.

Supercapacitors

Supercapacitors are very-high-capacity electrolytic devices that store energy in the form of electrostatic charge. They are composed of two electrodes with a very thin separator. Energy storage capacity increases as the surface area of the electrodes increases. Energy is stored as a DC field in the supercapacitor, and the system uses power electronics to both charge and discharge the capacitors. Supercapacitors can have very high discharge rates and could handle fast load changes in a MicroGrid.

A.3 Inverter Interfaces

There are two basic classes of microsources: DC sources, such as fuel cells, PV cells, and battery storage; and variable high-frequency AC sources such as a microturbines, whose output is converted to DC. In both cases, the DC voltage that is generated needs to be interfaced to the AC network and its loads. Power electronics provide this interface as a converter periodically switches the DC voltage polarity on the AC side to create an AC waveform of desired magnitude and phase.

A basic understanding of power electronics requires understanding of the creation of waveforms of different magnitudes, phases, and frequencies using circuits containing rapidly acting switches and energy storage elements. Power electronic devices are designed to operate like switches, but, because these devices are made of semiconducting materials like silicon, they can function much more rapidly than mechanical switches. Energy storage elements, such as inductors and capacitors, filter the sharp-edged waveforms created by the switching.

Voltage-Sourced Inverters

A circuit and switching sequence is needed that can convert the DC voltage from a microsource to three-phase AC voltage. Consider the circuit in Figure A3.1(a). On the left is a DC voltage that is provided by the microsource and connected to a three-phase AC system using double-pole switches. In reality, these switches are power electronic devices with bi-directional current flow capability and rapid switching speeds. In the current positions (1,6,2), the three-phase line-to-line voltage is: $V_{AB} = V_{DC}$, $V_{BC} = 0$ and $V_{CA} = -V_{DC}$. This strategy allows the converter to synthesize three AC square waves of voltage at the correct phase to each other. Figure A3.1 (b) shows the V_{AB} synthesized square wave. The positive voltage is achieved by the switch positions shown (1,6); negative voltage requires the opposite (3,4) position.

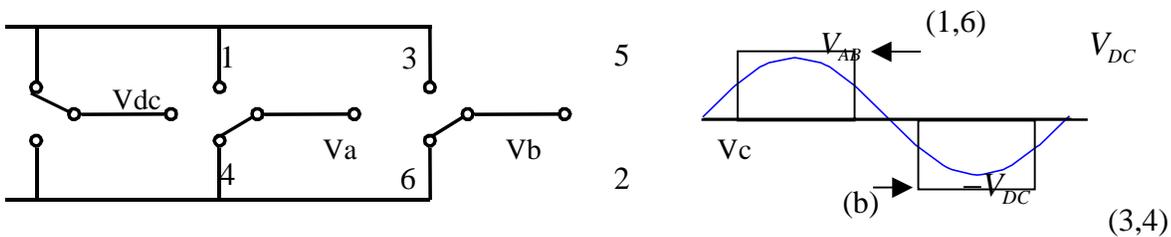


Figure A3. 1 Voltage Synthesis (a) Circuit, (b)Line-to Line Voltage

Although a square wave allows full control of rms voltage output and phase, it would require a great deal of filtering to provide the loads with the required sinusoidal waveforms. Power electronic switching devices have the ability to switch much more rapidly than the fundamental frequency, which means that *pulse width modulation* (pwm) is an option. For example, for the positive voltage section, Figure (b), the inverter can rapidly switch from the (1,6) position to the (1,3) or (4,6) position, which provides zero voltage between phases A & B. The same can be done on the negative side. This allows the instantaneous average output to be held closer to the desired fundamental output. A converter incorporating pulse width modulation requires considerably less filtering to achieve the required power quality.

In general, pulse width modulation is limited by the switching frequency of the power electronic device and the techniques of the controller. Typical switching frequencies are at least 30 times faster than the fundamental frequency. During each switching period, the inverter control selects the times of conduction or duty cycles that create the desired voltage for that period. The resulting voltage is made of pulses of different widths (hence the name pulse width modulation). The pattern and number of pulses are designed to provide the required voltage magnitude, and the pulses are placed to minimize the harmonic content. Such a pattern is shown in Figure A.3.2 for all three phases. The arrows indicate the switch position shown in Figure A.3.1 (a).

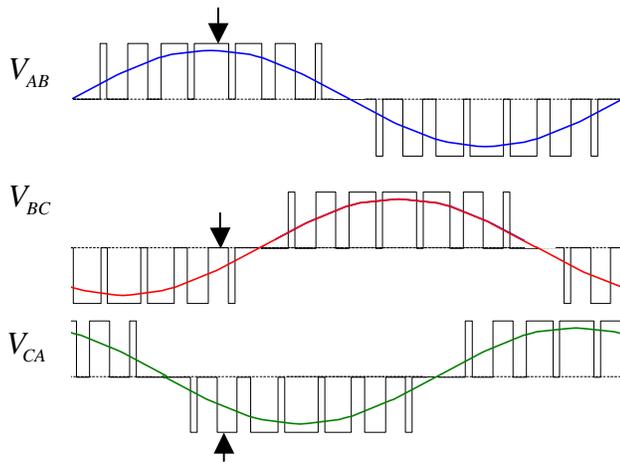
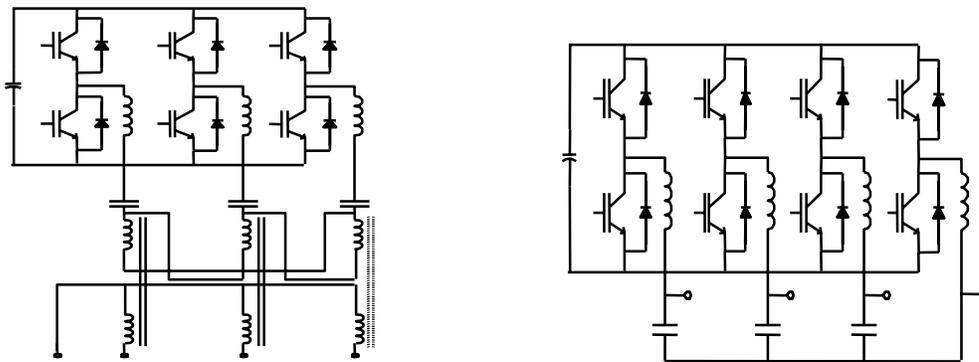


Figure A.3. 2. Three-Phase Pulse Width Modulated Voltage

Inverter Realization for Microsources

To realize an actual voltage-sourced inverter with pwm, two key issues must be addressed: implementation of switches and connection to the customer’s AC system. The switches shown in Figure A.3.1 are implemented using Insulated Gate Bipolar junction Transistor (IGBT) and diodes. The advantages of IGBTs include their simple gate drives derived from voltage control requirements and their ample voltage/current ratings up to 3,000 volts and 1,200 amperes. Their switching times are less than one microsecond. IGBTs with reverse diodes are shown in place of switches in Figure A.3.3.



FigureA3. 3. PWM Inverters with Four- Wire Interface, (a) Using Star-Delta Transformer (b) Direct connection using four- legged Inverter

Microsources such as microturbines, fuel cells, and PV systems seldom exceed 200 kilowatts and in many cases are smaller than 100 kilowatts. This low level of power along with the need to utilize waste heat means that these sources are placed at the customer’s site rather than at the utility’s substation. AC systems are usually 480 volts or less with a four-wire configuration to

accommodate single-phase loads. This requirement can be met using the three-legged inverter shown in Figure A.3.1 with the addition of a star-delta transformer' the center point of the star can be used to provide the extra wire [see Figure A.3.3 (a)]. Another possibility is to add a fourth leg to provide the extra connection point [see Figure A.3.3 (b)]. The operation is similar to one discussed in the section on voltage-sourced inverters above except that the DC voltage is always switched between the neutral and single- phase. This allows for direct creation of phase-to-neutral voltages rather than line-to-line voltage provided by a three-legged inverter. The differences between the two circuits in Figure A.3.3 include: the use of magnetics versus extra IGBTs and diodes, and the handling of fault current and dependents between DC and AC voltage levels. During a fault, fault current will be flowing in the four-legged inverter; in transformer-coupled systems, the fault current will circulate in the delta winding. For the transformer-coupled system the DC voltage becomes a free variable because of the turns ratio. In the direct-coupled system the DC voltage needs to be 10 to 20 percent larger than the required peak AC voltage.

Unbalanced AC Voltages

Microsources with AC voltages of 480 volts or less and a four-wire configuration to accommodate single-phase loads have unbalanced voltages because of asymmetries in the wiring and the presence of unbalanced loads. When these microsources are connected to the AC system using the inverters discussed above, there will be uneven phase currents. However, microsources may be intolerant of voltage imbalances. Field experience with ONSI fuel cells, for example, has shown that imbalances trip the current protection in the inverter because it assumes balanced currents. (This is the norm for adjustable-speed-drive protection).

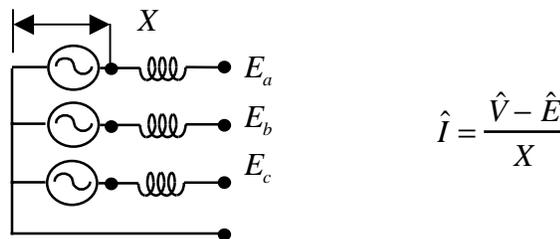


Figure A.3.4. Basic Four- Wire Source

Both inverters shown in Figure A.3.3 can be represented as shown in Figure A.3.4 to demonstrate interactions with the AC system. The voltage-sourced inverter creates three AC voltages, $V_{a,b,c}^{inverter}$ that are coupled to the AC system through three inductors, X . The current that flows in each inductor is dependent on the inverter and AC system voltages. If the AC system voltages are balanced and the inverter creates balanced voltages, the currents are equal. When the AC voltages are unbalanced, the currents also become unbalanced. The inverter has the flexibility to create unbalanced voltages between phases that can:

- Rebalance the output currents,
- Correct the system's voltage imbalance,
- Regulate the positive sequence AC voltage but not correct for the imbalance, and
- Remove the negative sequence AC voltage component that results from a voltage dip.

In general, voltage-sourced inverters have the flexibility to deal with most unbalanced situations seen in the field, but this flexibility is not currently used. The Honeywell Parallon 75 uses the system shown in Figure A.3.3(a). It can control power and reactive power flow. In situations where AC voltages are unbalanced, the currents are also unbalanced and will trip at 20 percent overcurrent in the delta winding. The Capstone 330 uses the system in Figure A.3.3(b). In island mode, the unit provides balanced three-phase system voltages. The currents are a function of the load imbalance, and the system trips when the neutral line has a power flow above one-third of the system's power rating. For highly unbalanced loads, the total output could be less than one-third the rating of the microturbine.

A4. Combined Heat and Power (CHP)

Combined heat and power (CHP) technologies, also known as cogeneration, produce electricity and heat simultaneously. This is accomplished by capturing and using the roughly two-thirds of heat that is produced and typically rejected in electricity production. As a result of this waste heat use, the overall energy efficiency of CHP systems is substantially greater than that of systems that do not have this feature.

CHP systems are more prevalent in many economies than in the U.S., where they are only commonly found in industrial facilities. For example, as of 1996, 48 percent of the domestic electricity demand in Denmark came from CHP plants. This level of CHP is believed to reduce CO₂ emissions by approximately 7-10 Mt per year, or more than 10 percent of the total CO₂ emissions of the country, compared with emissions from separate heat and power production. CHP units that are 2-4 MWe are typically the best size for Danish local district heating systems, which power approximately 100-250 households and two large institutions or a net heat demand of approximately 20 TJ. Elsewhere in Europe, the Netherlands produces about 30 percent of its power from CHP systems, Germany produces about 14 percent, and Italy produces about 12 percent. By comparison, the U.S. produces only about 9 percent of power from CHP systems. On a scale more relevant to MicroGrids, more than 2,500 CHP units with capacities between 100 and 300 kW have been installed in the Netherlands in hospitals, community buildings, schools, and businesses .

Unlike electricity, heat, usually in the form of steam or hot water, cannot be easily or economically transported long distances; therefore, typical CHP systems provide thermal energy for "local" services such as space heating or cooling, process heat, refrigeration, water heating, or local district heating. To make such systems viable, a sufficiently large need for heat must exist within a sufficiently dense area so that circulation of steam, hot water, or another appropriate medium is feasible and economic. CHP systems installed in a MicroGrid could capture two significant advantages over CHP systems in independent installations:

1. MicroGrid heat production is small scale and therefore can be well matched to requirements. That is, a MicroGrid should be constructed from the most economic combination of waste-heat-producing generators (e.g., high-temperature fuel cells and microturbines) and non-waste-heat-producing generators (e.g., windmills or PV modules) so that joint generation of electricity and heat is optimized overall. In other words, the total joint cost of supplying the

heat and electricity needs of the facility served by the MicroGrid should be minimized. End-use energy efficiency will play a critical role in maximizing the system energy efficiency.

2. In a MicroGrid, the production of heat can move close to its use. In an extreme example, a high-temperature fuel cell could be placed on each floor of a hospital to provide the hot water needs of the floor. Because electricity is more readily transported than heat, generation close to the heat load will usually make more sense than generation close to the electrical load. (The same principle holds with large power plants, which tend to be sited close to sources of cooling water but distant from the users of their power.) Because the MicroGrid permits small, diverse generators to operate in a passively coordinated manner, generators can be optimally placed relative to loads.

Low-Temperature Heat Use

The application that comes most readily to mind, as a useful waste-heat sink in small-scale, on-site generation systems is low- and moderate-temperature water heating. In the industrial sector, any number of applications is possible. In the commercial sector, the primary options are direct hot water use, e.g., restaurant dishwashing, sterilization, and space heating. Commercial hot water usage tends to be concentrated at a limited number of sites, such as hospitals and restaurants, which are promising hosts for power generation that would be delivered to neighboring MicroGrid customers that have minimal heat requirements, such as stores, offices, and residences. Some analysts have emphasized the potential for small-scale systems to serve the residential sector. Space heating requirements vary significantly by season, location, and building occupancy, so the economics of this CHP application are likely to be highly variable. Most hot water and space heating applications are fairly low-tech, so there are few technical barriers to widespread adoption.

Certain energy-generating technologies are more applicable to CHP applications. Microturbines, for example, offer higher-temperature heat output than reciprocating engines and thus can provide greater benefits in cogeneration applications. Two European manufacturers, Bowman and ABB, are specializing in CHP microturbines. In the U.S., Capstone is offering a package system that captures waste heat from their microturbine and allows it to serve thermal loads. High-temperature fuel cells also provide premium heat for CHP systems. There is vast potential for improving the system design of electrical and thermal energy services in residential and commercial applications. More work is needed in the area of MicroGrid system design and operation, especially in tools for determining the optimal placement of heat sources subject to constraints imposed by safety and noise concerns.

Picture of a Capstone Microturbine with an attached CHP unit. Source: Capstone Turbine www.capstoneturbine.com



CHP Technologies

A number of technologies are used for CHP systems. A typical CHP system of less than one MW capacity consists of the following items: a technology to generate power, an alternator for electrical output, a heat recovery unit to generate thermal energy, a component to evacuate combustion products (if necessary), a control system, an electrical- protection and low-voltage connection box, and soundproof insulation. The method used to recover heat in a CHP system depends on the type and capacity of the technology used to generate power. The power generation technologies that are likely to be usable for CHP in MicroGrids are reciprocating engines, microturbines, and fuel cells.

Reciprocating Engines

Reciprocating engines come in many types; the two designs that are most likely to be useful in CHP systems are four-cycle spark-ignited (Otto cycle) and compression-ignited (diesel cycle) engines. Otto cycle engines ignite an air-fuel mixture in a cylinder using a spark plug. Diesel engines compress the air in the cylinder, raising the ignition temperature of the fuel, which is injected at high pressure.

Reciprocating engines typically have electrical efficiencies of 25 to 50 percent. The smaller stoichiometric engines that require 3-way catalyst after-treatment operate at the lower end of the efficiency scale while the larger diesel and lean burn natural gas engines operate at the higher end of the efficiency range. In a reciprocating engine, energy from the fuel is converted into mechanical drive power and heat, which is released through the engine jacket and combustion gases. Engine jacket heat is removed by a cooling fluid loop. Approximately 60 to 70 percent of the total input energy is converted to heat that can be recovered from engine exhaust and jacket coolant. Heat dissipated to the engine jacket coolant accounts for about a third of the input energy and can reach temperatures around the boiling point of water.

A closed-loop hot water cooling system is typically used for capturing engine heat. The coolant is circulated through the engine passages and an external heat exchanger. These cooling systems can operate at about 90 to 120°C and use a heat exchanger to send excess heat to a cooling tower.

Ebullient cooling systems circulate boiling coolant through the engine and are often used for producing low-pressure steam. The coolant is limited to 120°C or saturated steam conditions. System benefits include extended engine life and improved combustion efficiencies as a result of the uniform coolant circuit temperature.

Engine exhaust is responsible for about 10 to 30 percent of fuel input energy, providing temperatures of about 450–650°C, although only a portion of the exhaust heat can be recovered because the gas must remain above condensation point to avoid corrosive condensation in exhaust piping. Thus, most heat recovery units are designed for a 150° to 177°C exhaust outlet temperature. This heat can then be used to generate 110°C hot water or low-pressure steam at 15 psig. The end result is that about 75 percent of the reciprocating engines input energy is utilized. The recovered heat can be used for CHP processes such as space heating, domestic hot water, absorption cooling, and desiccant dehumidification.

Microturbines

Microturbines have capacities from 30 to about 250 kW. For larger capacities, microturbines can be combined, which also increases reliability. Microturbine design is simple and often has only one moving part, a shaft with attached compressor, turbine, and permanent-magnet generator spinning at high speeds on air bearings. Microturbines operate at speeds up to 120,000 rpm and can be powered by a variety of fuels including natural gas, gasoline, diesel, and alcohol. Microturbines typically include a recuperator that preheats the incoming compressed air and increases electrical efficiency. Recuperators also cool the exhaust gas, however, and thus limit the thermal energy available for use in CHP applications. Most microturbine manufactures include a recuperator bypass valve that reduces the electrical efficiency but increases overall system efficiency when waste heat is recovered. Microturbine efficiencies for power generation are typically about 30 percent, but the electrical efficiency falls to about half of that when the recuperator bypass is engaged although the overall thermal efficiency may rise to about 80 percent. The exhaust gas is typically at about 260°C while the recuperator is in use and 870°C when the recuperator is bypassed (E Source, 1996). Not all of the waste heat can be effectively transformed into useful energy.

High-temperature fuel cells can generate enough heat to produce steam for a steam turbine or microturbine, so combined-cycle power generation is possible, or waste heat can be captured by CHP, or both. Fuel cells operate by reverse hydrolysis, combining oxygen and hydrogen to produce electricity, heat, and water. Fuel cells produce DC current and heat using a chemical reaction rather than a mechanical engine driven by combustion and can operate as long as fuel is being supplied (in contrast to the fixed supply of chemical energy in a battery). Fuel cells can operate at electrical efficiencies of 40 to 60 percent (LHV), and up to 85 percent in CHP applications.

Some fuel cells release significant heat during operation; the quality of the thermal product depends on the type of electrolyte in the fuel cell. The phosphoric acid fuel cell (PAFC), which is commercially available, operates at moderate temperatures (approximately 200 °C) and produces low-pressure steam or hot water as a byproduct. Polymer electrolyte membrane (PEM) fuel cells are being developed primarily for transportation applications but may be used in stationary

power as well. They operate at relatively low temperatures to protect the membrane and thus have the least potential for CHP applications. Two promising fuel cell chemistries, molten-carbonate (MC) and solid-oxide (SO) fuel cells, operate at much higher temperatures (650 and 900 °C, respectively) and are expected to provide excellent combined-cycle and/or CHP opportunities. SO fuel cells are based on all-solid ceramic construction and are expected to be a particularly reliable technology with electrical efficiencies up to 50 percent.

Heat Exchangers

Heat exchangers are designed from different materials depending upon their application. Stainless steel is expensive and does not conduct heat well but holds up effectively against the corrosion from exhaust gas condensate. Heat exchangers can capture about 80 percent of the heat from exhaust gas and transfer it to an absorption chiller.

Cooling Technologies

In buildings in most areas of the U.S., cooling is required in addition to (and frequently more than) heating; this weather-sensitive and often peak load imposes high costs on the centralized power system. For example, in California, air conditioning is estimated to be responsible for about 29 percent of peak electricity demand, yet this end-use only consumes about 7 percent of the state's total electrical energy. Refrigeration, though it is much less weather sensitive and has a high load factor, represents an even larger share of total electricity consumption in California, about 8 percent. MicroGrids will be able to effectively provide the electricity required by these major end uses; even more exciting is the possibility of waste heat being used to provide cooling. Absorption cooling and desiccant dehumidification are two techniques for using waste heat to meet or reduce cooling loads.

Absorption cooling uses heat (in place of the mechanical energy required to run a compressor) to drive a refrigeration cycle. Absorption cooling cycles take advantage of chemical processes using a refrigerant and an absorbent that combine at low pressure and low temperature to form a solution. Water and lithium bromide or ammonia and water ($\text{NH}_3\text{-H}_2\text{O}$) are common refrigerant/absorbent combinations. The functioning of this technology is described using the example refrigerant/absorbent combination of water and lithium bromide: The absorber is kept at low pressure (0.1 Psia) so that the refrigerant (water) boils at 2°C. The refrigerant vapor is absorbed by the lithium bromide and becomes a saturated liquid, forming a solution and releasing heat during the saturation process. That is, the absorption process causes the refrigerant to become a liquid at under temperature and pressure conditions when it would normally be a vapor. The solution is then pumped to a device called a generator. The solution in the generator is at a higher pressure (0.9 Psia) and temperature (37°C) than on the absorber side of the cycle. Applying heat drives the refrigerant from the absorbent. The refrigerant passes through a filter, which keeps the absorbent on its side of the cycle, and into the condenser. The condenser is at the same temperature and pressure as the generator ; under these conditions, the refrigerant cools and becomes a liquid. It is then sprayed into the evaporator, where it expands to a gas because of the low pressure. As the refrigerant becomes a vapor, it picks up latent heat from its surroundings, producing a cooling effect.

Absorption cooling systems have been used for some time, but they are inefficient compared to compressors, typically having a coefficient of performance (COP) of up to 0.7 for single-effect chillers. The efficiency of these cycles is being increased by developments that permit the capture and use of more of the rejected heat from the cycle, with multiple cycles at lower temperatures. Methods of increasing the efficiency of absorption cooling by adding additional generators and condensers to utilize remaining heat from the primary generation process are called double-effect and triple-effect chillers and can have COPs of 1.1 and 1.5 respectively.

The fluid used as a heat input should have a temperature of about 90°C to drive a single-effect absorption chiller and temperatures between 120° and 150°C to drive a double-effect absorption chiller system. Absorption chillers are driven by hot water or steam from a rejected heat loop, or direct fired from a natural gas or propane burner. The direct-fired units are all double-effect systems because of the high temperature of the gas (1200°C).

One major benefit of absorption cooling is that it can reduce the cooling load that often causes a customer's daily and seasonal peak energy demand and is the most expensive load to meet. Even if the MicroGrid is not paying a true real-time price, lowering peak energy use may substantially reduce demand charges and provide immediate reductions in customers' utility bills. Absorption cooling also allows more efficient and economical use of on-site generation and refrigeration and can provide a year-round use for the heat produced by electricity generation.

Desiccant dehumidification and cooling removes latent heat load (or moisture) from the air. This helps reduce cooling loads and allows air conditioning systems to operate more efficiently. Conventional cooling systems dehumidify the air by using a cooling coil that is cold enough to condense water out of the air. This requires more energy than would be required for sensible cooling alone. Desiccant systems can reduce heating, ventilating, and air conditioning (HVAC) electricity use by 30 to 60 percent and peak electricity demand by 65 to 70 percent (E Source, Space Cooling Technology Atlas, 1997). Payback periods for desiccant systems typically range from two to four years (E Source Tech Update, 1998).

Desiccant systems work by using a material that absorbs moisture from the incoming air flow. The desiccant is then rotated to a warm air stream to be heated and dried. DER can provide a source of heat for desiccant systems and can thus help reduce the energy use of the cooling system.

Cost of desiccant systems have been prohibitive in the past but are declining and in some applications are offset by the savings from reduced cooling costs. The economic benefit of desiccant dehumidification is a function of the particular application and the potential benefit from humidity control, and the summer humidity level and the electricity tariffs in a given area. Desiccant systems are suited for applications where humidity control is important. These include museums, supermarkets, hotels, hospitals, some industrial facilities, and other types of buildings in humid areas.

APPENDIX B. Electrical Environment for MicroGrids

B. 1 Interconnection Issues

DER has gained increased attention as electrical power supply and demand issues have become more urgent. At the center of these issues is the need for additional power generation and the ability to transmit greater amounts of power to end users. Historically, investments in infrastructure -- new generation and associated transmission and distribution (T&D) systems -- have followed expanding power needs. However, in recent years these investments have not kept pace with rising demand, resulting in shrinking reserves and transmission systems operating near their limits. During the same time period, advances in technology have substantially reduced the cost of DER, so, for the first time, they are being seriously considered as a solution to growing power needs.

DER consist of many electric power resources distributed throughout lower-voltage power distribution systems. These resources are typically small generators, but they can also be energy storage devices or non-conventional power sources such as PV or fuel cells. As implied in the definition, the power produced by DER does not travel over the high-voltage transmission grid prior to being delivered to end users. In most cases, DER are located very close to the power loads it serves, but power from DER could be injected into the lower-voltage distribution system. In principle, this power could make its way into the high -voltage electrical transmission system, but, in practice, it typically serves loads in near its point of generation.

Current Integration Standards for DER

Local interconnection standards vary considerably from one utility to the next. A national standard is being drafted by the IEEE SC21 working group. ANSI standard P1547 (Draft) Standard for Distributed Resources Interconnected with Electric Power Systems does not use the term "MicroGrid," but it addresses a group of DER as a Local Electric Power System (LEPS). The standard accounts for the issue of a LEPS connecting to the utility grid (Area Electric Power System or AEPS) by focusing on the aggregate DER rating of the LEPS. As a result, the rules applied to a MicroGrid containing many small DER are the same as for a single large distributed energy source. P1547 applies only to single or aggregate DER of 10 MVA or smaller. Although IEEE draft Standard P1547 allows safe and reliable integration of DER into radial distribution systems with minimal immediate economic costs, it does not provide a means for DER to operate separate from the utility grid.

System Protection

A typical radial distribution system has been assumed in the discussions that follow; we also assume that DER are integrated with this distribution system in accordance with IEEE draft P1547. The changes that would be required in existing protection schemes are outlined below.

Transformer Protection:

- Transformer Fault: Connecting the MicroGrid to a utility grid would not affect the ability of the utility's differential protection scheme to detect and/or isolate a transformer fault. No adjustments to this protection would be necessary.

Line Protection:

- Ground Fault on the Feeder: DER that are connected to the faulted phase would contribute to the fault and thus reduce the fault current seen by the AEPS. However, at the inception of the fault, all but the lowest rated DER (on all phases) would detect the fault and separate from the system per IEEE P1547. After the DER separate, the fault current contribution from the AEPS would increase and feeder protection would enable, just as though DER had never been connected to the feeder. The fault detection time might be prolonged because of the presence of DER, but the protection scheme would not need to change. IEEE P1547 would require DER to comply with local rules regarding reclosing coordination. A reasonable approach for this coordination would be for the utility to require DER units that have tripped off line to remain off line for a period of time that exceeds all disturbance and reclosing events (e.g., five minutes). These requirements would have little impact on existing system protection.
- Line-to-Line Fault on the Feeder: For DER connected to the faulted line, the voltage seen at the DER terminals would, in most cases, be out of the allowable operating band specified in P1547, so the DER would trip off line. DER operating on the unfaulted phase during a line-to-line fault would, in most cases, also exhibit voltage outside of the allowable operating band specified in P1547 and would thus trip off line. If the unfaulted phase voltage did not move outside the allowable operating range, detection of the fault by the utility would not be impeded by operation of DER. Thus all phases of the feeder would be tripped per the utility's normal protection scheme. At that point, all DER that remained connected would sense voltage outside of the allowable operating range and would immediately disconnect.

Voltage Regulation

Many distribution transformers include load tap changers (LTCs), which adjust the transformer's turns ratio based on the load current and thus influence voltage regulation. As DER units were placed on line or off line, the LTC would see more or less current and adjust the transformer's voltage output to compensate for the voltage drop of the feeder. If DER were sited away from the LTC, then, as the DER were turned on, the feeder's voltage profile would benefit by flattening out. However, if DER were located very close to the LTC, they would have an undesirable effect on the feeder's voltage regulation, which would have to be remedied by adjustments to the LTC or by other means. For distribution systems that do not use LTCs, the integration of DER might cause voltage regulation problems that would need to be addressed by a permanent tap change to the distribution transformer, the addition of an LTC, or other means. However, if the MicroGrid is designed correctly, the voltage at the interfacing point will be constant over a large range of loads and should greatly reduce the problems of LTCs.

Next-Generation Distribution Systems

Although the IEEE standard permits integration of single DER into radial distribution systems, it does not allow all of the potential benefits of DER to be realized. The benefits that would not be possible under the standard as it is currently drafted include:

- Increasing system reliability by relying on power supplied to customers by both DER and the transmission grid (because P1547 requires DER units to disconnect from the utility when a disturbance occurs),
- Allowing the aggregate load within a distribution system to exceed the rating of its interconnection to the transmission system,
- Regulating voltage by utilizing DER voltage control,
- Enhancing system stability by providing reactive power support to loads within the distribution system,
- Permitting “islanded” operation, which would allow sections of a distribution system to continue operating at the same time that a faulted section is isolated.

The MicroGrid is designed to provide all of these benefits to its own customers in addition to meeting the above restrictions for the distribution system.

Distribution Area Monitoring and Control

Integrating DER so that they can provide the benefits outlined above will require overhauling the conventional distribution system so that it functions similarly to the traditional transmission system. The key ingredients of this overhaul would be as follows:

Frequency Supervision: When DER separate from the transmission grid, no frequency “leader” exists for them to follow. Therefore, a real-time, global signal must be sent to DER to constantly set and synchronize the frequency at which they generate power.

Dispatch Control: In any closed power system, the power generated must equal the power used. Controllers or governors can control the power generated up to a point beyond which more available generation must be dispatched to meet demand. A control system is needed to automatically dispatch generation when system load approaches available generation.

Load-Shedding Control: If demand exceeds all dispatched generation, loads must be de-energized or the system will become unstable. A controller is needed to systematically de-energize loads when sufficient generation is not available for dispatch.

Voltage and Reactive Power Support: DER must establish and support system voltage. Voltage support is needed to regulate voltage throughout the distribution system. Reactive power control is also needed to ensure system stability.

Synchronizing capability: An isolated distribution system must be able reattach to an energized transmission system without an interruption in service. Likewise, isolated DER must be able to reattach to an energized distribution system.

Dynamics Management: If MicroGrids are to operate isolated from the utility grid, they must have sufficient means to stabilize system disturbances. Typical power systems automatically store energy reserves in their rotational kinetic energy, which can absorb energy from or add energy to the system. However, most DER within a MicroGrid are expected to be based on power electronics, so they will have no rotational kinetic energy. When a disturbance occurs in an isolated MicroGrid, the system is constrained to match generation with loads. Without a power repository equivalent to system inertia, the MicroGrid would need to correct this mismatch in such a way that further system voltage or frequency suppression would result, leading to loss of loads and instability of the system. Although the rotating loads within a MicroGrid do have inertia, the loads themselves will likely be insufficient to mitigate these dynamic concerns. Ensuring that MicroGrids maintain system stability will not be a matter of simply following past practice.

B.2 Customer Systems

Customer systems can contain DER connected to a 35-kV, 25-kV, 13.8-kV, or even 2.2kV distribution system. It includes step-down transformers and a 480-V or 208-V system (secondary distribution system) that may be radial or networked. A single-line diagram of a radial system is shown in Figure B.2.1. A single-line diagram of a networked system is shown in Figure B2.2.

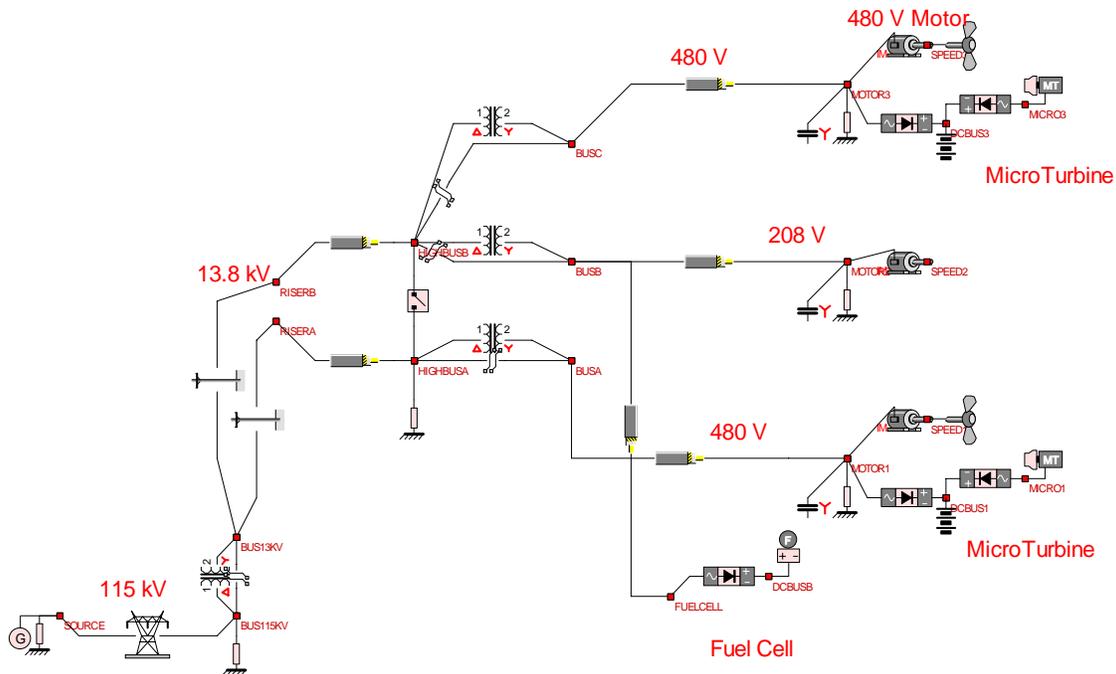


Figure B2.1 Conceptual Single-Line Diagram of a Radial MicroGrid

A MicroGrid may have three-, two-, or single-phase connections to the utility distribution system. The various possibilities are shown in Figure B2.3. The main circuit is a five-wire system with three phases, a neutral, and a ground conductor. The ground conductor is grounded at multiple points, and the neutral is grounded at the source end of the circuit. Part of the MicroGrid may be connected to the utility distribution system by three-phase transformers (typically delta-wye connected, delta on the utility side), and part of the MicroGrid may be two phase or single phase. Two-phase and single-phase systems are generated from tapping to the utility distribution system phase-to-neutral or phase-to-phase. The exact connections are described in the sections below on wiring practices and grounding and bonding.

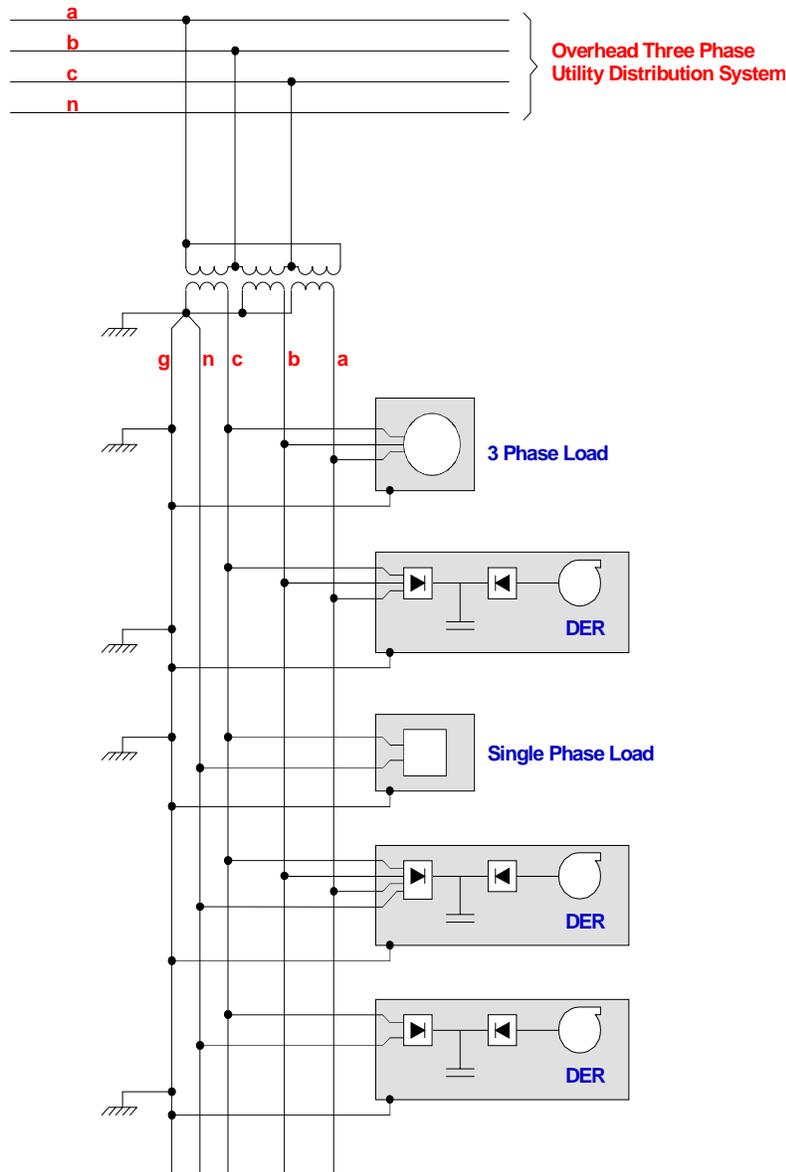


Figure B2.3 Illustration of Possible MicroGrid Topologies

Wiring Practices

Wiring practices for secondary distribution systems are dictated by the National Electrical Code and prudent engineering design. For three-phase systems, the best practice is a five-wire, three-phase circuit with a neutral and a ground conductor. If metallic conduit is used, the ground wire may be omitted, or, if the ground conductor is included, it may be bonded to the conduit. The size of the phase conductors and neutral are selected based on the rated amperage of the device. The neutral is normally the same size as the phase conductors or one size smaller. In cases of substantial imbalance or substantial zero sequence harmonics, it may be necessary to have a neutral that is larger than the phase conductors.

Grounding and Bonding

Grounding arrangements depend on the number of wires and voltage transformations. Figure B2.4 illustrates a system with two voltage transformations; Figure B2.5 illustrates a system with one voltage transformation. The National Electrical Code and good engineering practice require that the system be grounded at least once for each derived system. A derived system is generated with a voltage transformation. Each derived system can be a three-wire system (three phases only), or a four-wire system (three phases and a neutral, or three phases and a ground conductor), or a five-wire system (three phases, a neutral, and a ground conductor). Typical practice dictated by the National Electrical code, is to ground the neutral conductor at the source location. If a ground conductor is used, it should be grounded at multiple points. The National Electrical code permits the neutral conductor to be grounded at more than one location in specific cases.

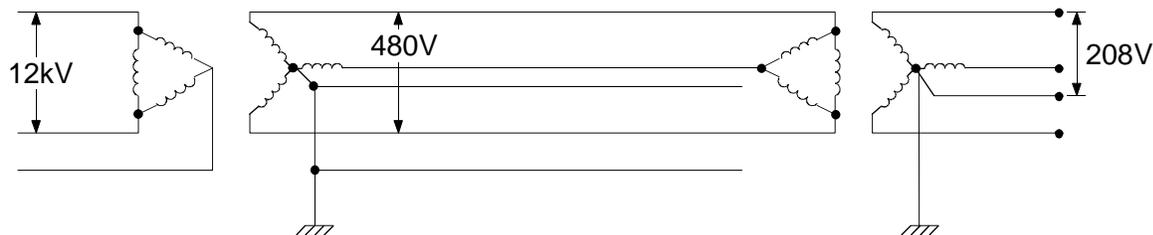


Figure B2.4 Distribution System with Two Voltage Transformations

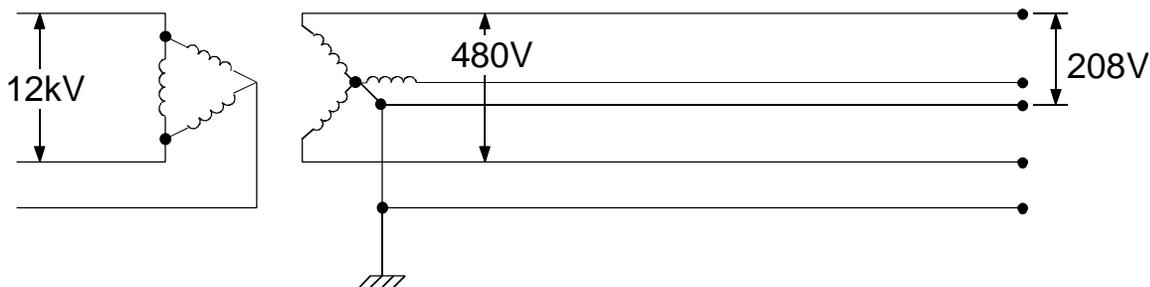


Figure B2.5 Distribution System with One Voltage Transformation

Standards

The applicable standards for customer systems are: the National Electrical Code, the National Electrical Safety Code, IEEE Std 80, FIPS Pub 94, Standard P1100, and draft standard 1547. Additional standards cover specific issues related to secondary distribution systems.

B2.2 Unbalanced Voltages and Loads, Stray Currents and Voltages

Customer loads may be three phase or single phase. Single-phase loads are typically connected phase to neutral, which generates voltage imbalances. The presence of induction motors can amplify imbalances. To minimize imbalances, induction motors should be on separate circuits if possible. Techniques for controlling imbalances and stray voltages and currents in conventional systems consist of: using a transformer as a buffer between the system and the imbalance generating load, increasing the size of the neutral, and enhancing the grounding system and therefore decreasing the ground impedances. MicroGrids provides an added opportunity for controlling imbalances and stray voltages and currents. The possibility of using DER to mitigate these problems will be discussed below.

Sources of Imbalance

The sources of imbalance in a MicroGrid are single-phase loads, distorting loads, and circuit asymmetries.

It is well understood that single-phase loads make three-phase currents unequal. The unbalanced currents generate unbalanced voltages because the voltage drop in the various phases will be unequal.

In secondary distribution circuits (480 V or 208 V) it is common to have loads that distort the sinusoidal waveform of the voltages and currents; i.e., they generate harmonics. The harmonic currents generated by distorting loads are often not of positive sequence (i.e., balanced currents). Most distorting loads may generate negative and/or zero sequence harmonics. Both negative and zero sequence currents contribute to the system imbalance.

Finally, circuit asymmetries generate imbalances in the system. A circuit is asymmetric if the flow of a balanced set of electrical currents through it generates three-phase voltages that are unbalanced. Most practical circuits are asymmetric. The degree of imbalance in a typical practical system may be up to six percent, measured as the percentage difference among the three phases. Attention to the placement and arrangement of the three phases can minimize the asymmetry of the circuit and the resulting imbalance.

In a typical customer system, all three sources of imbalance are present. The relative degree of the imbalance and the specific contributions from each source depends on the system.

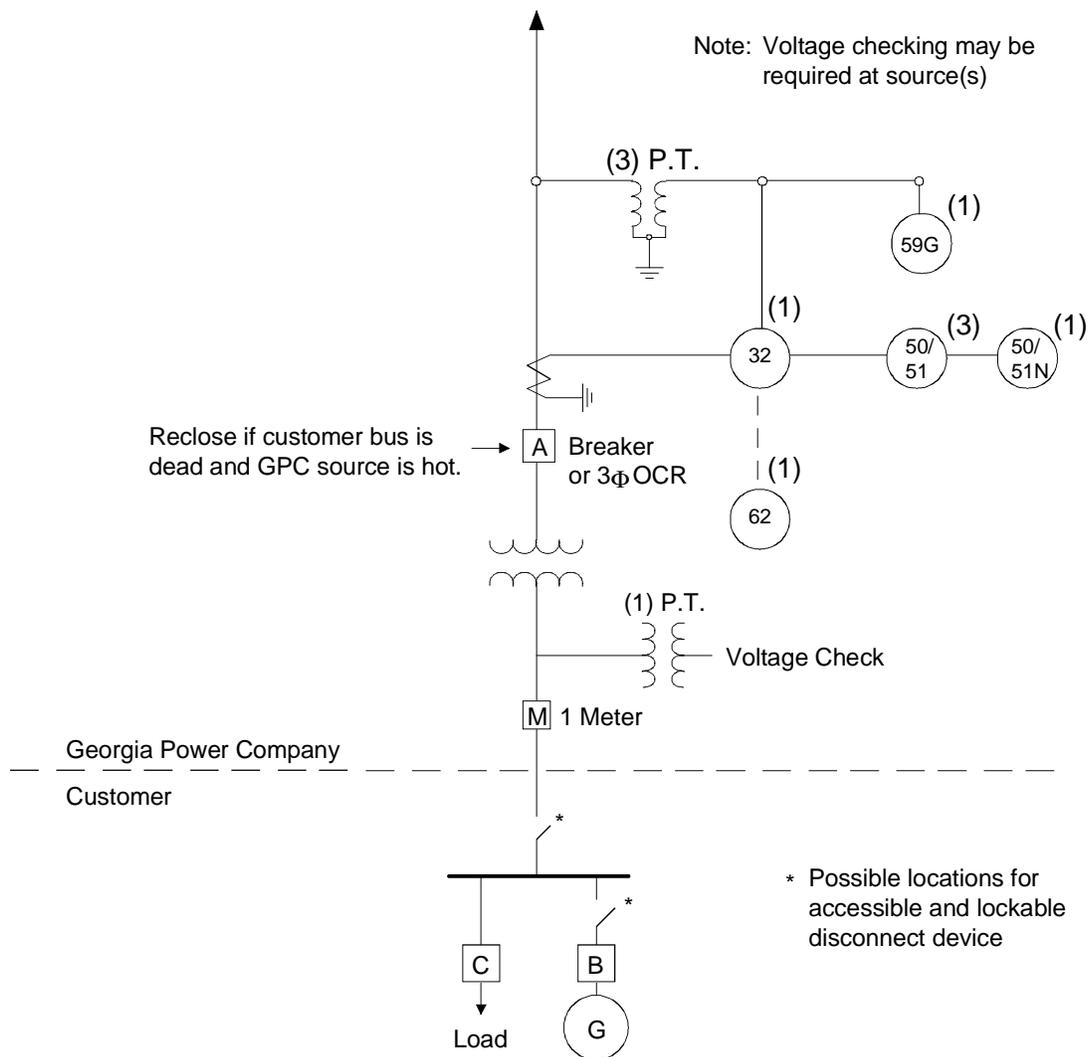
Effects of Imbalance on End-Use Equipment

The effects of imbalance on end-use equipment are uneven phase heating and accelerated aging of the equipment, and interference with the controls of intelligent devices such as converters and relays.

Uneven phase heating

Uneven heating of the three phases occurs when the electric current magnitude is different in each phase. In this case the device must be derated for the purpose of keeping its maximum operating temperature within its specifications. This effect can occur in cables, motors, transformers, etc. The required derating is computed on the basis that the ohmic losses in any one phase of the device will not exceed the rated losses. In certain cases, the interaction of the imbalance and the device operation result in increased electrical current imbalance. In this case, the current in the three phases of the device may be much more unbalanced than the imbalance in voltage. Induction motors have this characteristic; a small voltage imbalance in an induction motor may result in a much larger current imbalance and therefore substantial derating of the motor. As an example, Figure B2.6 shows a typical customer system with induction motors. Figure B2.7 illustrates the terminal voltages and current for the motor that is located in the lower right corner of Figure B2.6. Note that the terminal voltages have a 1.94 percent imbalance, and the electric current imbalance is 6.17 percent. This operating condition will result in an eight percent derating of the induction motor.

GPC Distributiob System (25 kV and below)



Device No.	Function	Trips
32	Reverse Power	Starts Timer 62
62	Timer for 32	A
59G	Zero Sequence Overvoltage	A
50/51	Phase Overcurrent	A
50/51N	Ground Overcurrent	A

Figure B2.6. Interconnection Requirements Defined by Georgia Power Company in their Document “Guide for Interconnection Requirements and Parallel Operation of Customer Generation (Courtesy of Georgia Power Company).”

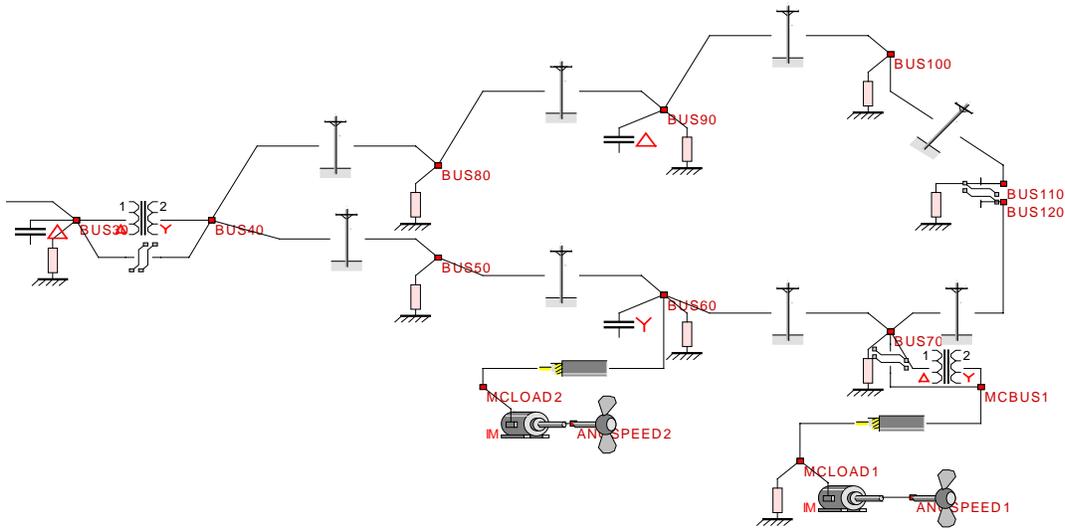


Figure B2.6 A Customer System with Induction Motors

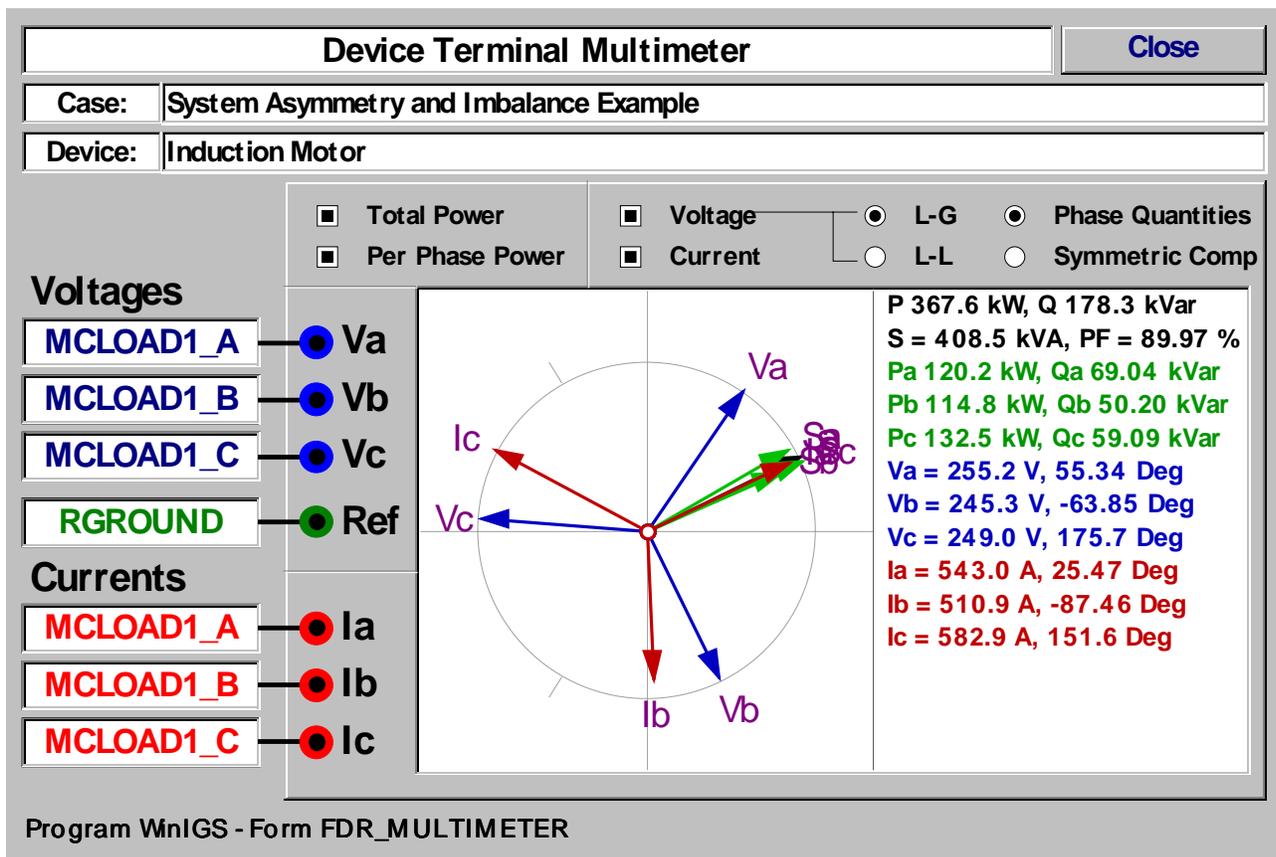


Figure B2.7 Illustration of Uneven Induction Motor Loading because of Imbalance

Interference with controls

Much new electronic equipment monitors imbalances and interrupts operation when an imbalance exceeds a certain level. This is very important for MicroGrid operation because most current products are designed so that inverters and therefore microsources will be disconnected when imbalances exceed a certain threshold.

Imbalance Mitigation Methods

There are many ways to mitigate imbalance. Below we summarize some key strategies, but this discussion is not exhaustive.

Load balancing

Load balancing entails distributing single-phase loads to the three phases in such a way that each phase will have approximately the same amount of load. Because, in general, electrical loads are not very predictable, the method does not always effectively balance the three phases.

Use of transformers

Connecting single-phase loads to two phases using transformers, as shown in Figure B.2.8, minimizes imbalance. In this case, the single-phase load current is converted into positive-sequence and negative-sequence current that reduces imbalance as compared to a direct, single-phase connection. Using transformers in combination with load balancing is an effective way to mitigate imbalance. In general, insertion of a transformer, three phase or single phase, tends to mitigate imbalance.

Circuit symmetry

Use of symmetric circuits also minimizes imbalance. Circuits can be made symmetric by twisting the three phases continuously and/or making sure that the three-phase arrangement is symmetric (for example, a triangular arrangement with the neutral in the middle).

Stray Currents and Voltages

Imbalances generate electric current flow in the soil because the distribution system and MicroGrid are grounded at multiple points; therefore, whenever there is imbalance, some of the unbalanced current will flow into the soil. Specifically, in systems with multiple ground neutrals, the grounds connect the neutral in parallel with the earth. (The National Electrical Code permits the grounding of a neutral in more than one place under certain conditions). In this case, any unbalanced current that may flow in the neutral will partially return through the earth. Practitioners refer to the currents that flow in the earth as stray or objectionable currents. The advantage of this grounding arrangement is that the overall impedance of the parallel combination of neutral and earth paths and ground conductors is lower. Stray or objectionable currents are harmless if the system is properly designed. The only disadvantage is that this effect interferes with ground fault protection.

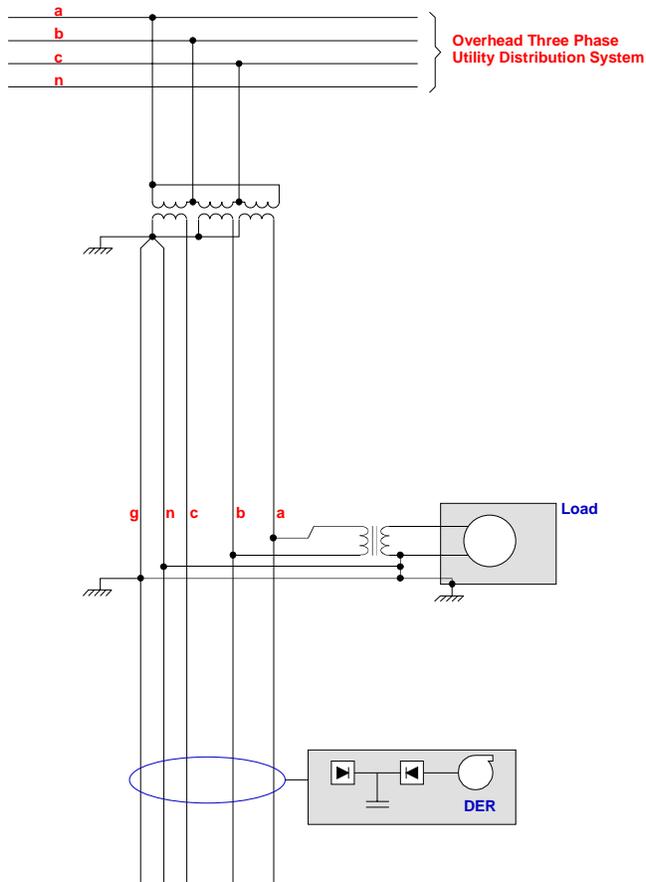


Figure B2.8. Use of Transformers to Mitigate Imbalance

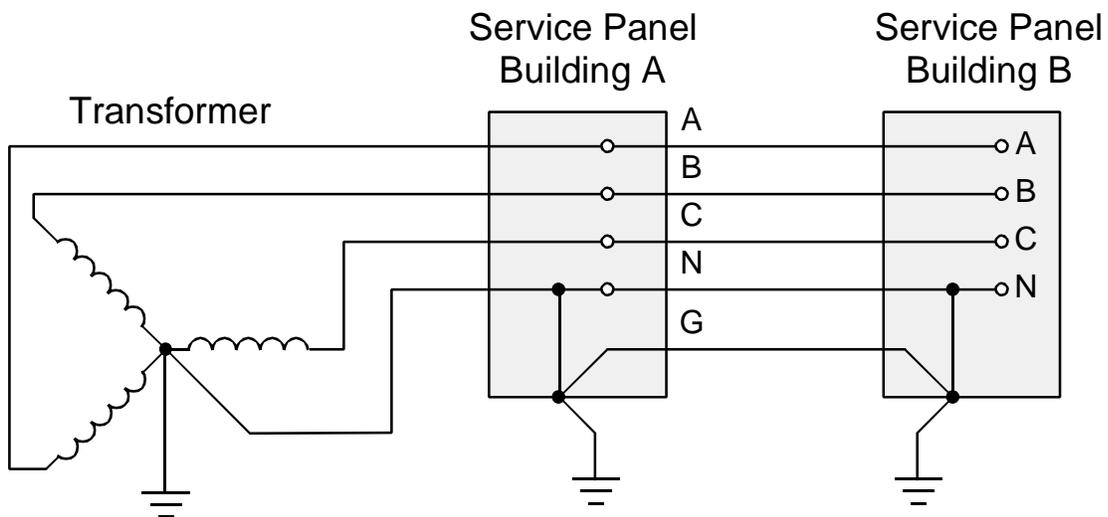


Figure B2.9. Illustration of Stray Voltages and Currents Generation

B2.3 Power Electronic Interactions

Customer systems may have complex interactions with power electronic devices. The level and effects of interaction depend on the dynamics of the customer system. One way to characterize customer systems is by frequency scans that determine the impedance of the system at a specific point as a function of frequency. Frequency scans reveal that customer systems are in general asymmetric; i.e., the impedance of one phase may be quite different from the impedance of another, as described below. Asymmetries can generate non-characteristic harmonics resulting from the interaction of converter controls and the system. The power electronic interface of DER can be used to control and mitigate these interactions, which depend on system impedances as a function of frequency. Customer systems may also exhibit a number of harmonic resonances. The presence of harmonic resonance conditions may amplify the interaction of inverters and the system. In a typical system there may be multiple harmonic frequencies.

System asymmetries can be revealed by frequency scans of each individual phase. For a symmetric power system, the impedance of a specific phase versus frequency will be the same for each one of the three phases. An asymmetric system will display differences. As an example, Figure B2.10 provides the frequency scan for a typical customer system of phases A and B of a specific three-phase bus. This system is quite asymmetric. The indicated impedance at 123.2 Hz is 0.7537 ohms for phase A and 0.7115 ohms for phase B, a difference of about six percent. This asymmetry will affect the performance of the power electronic interface of DER.

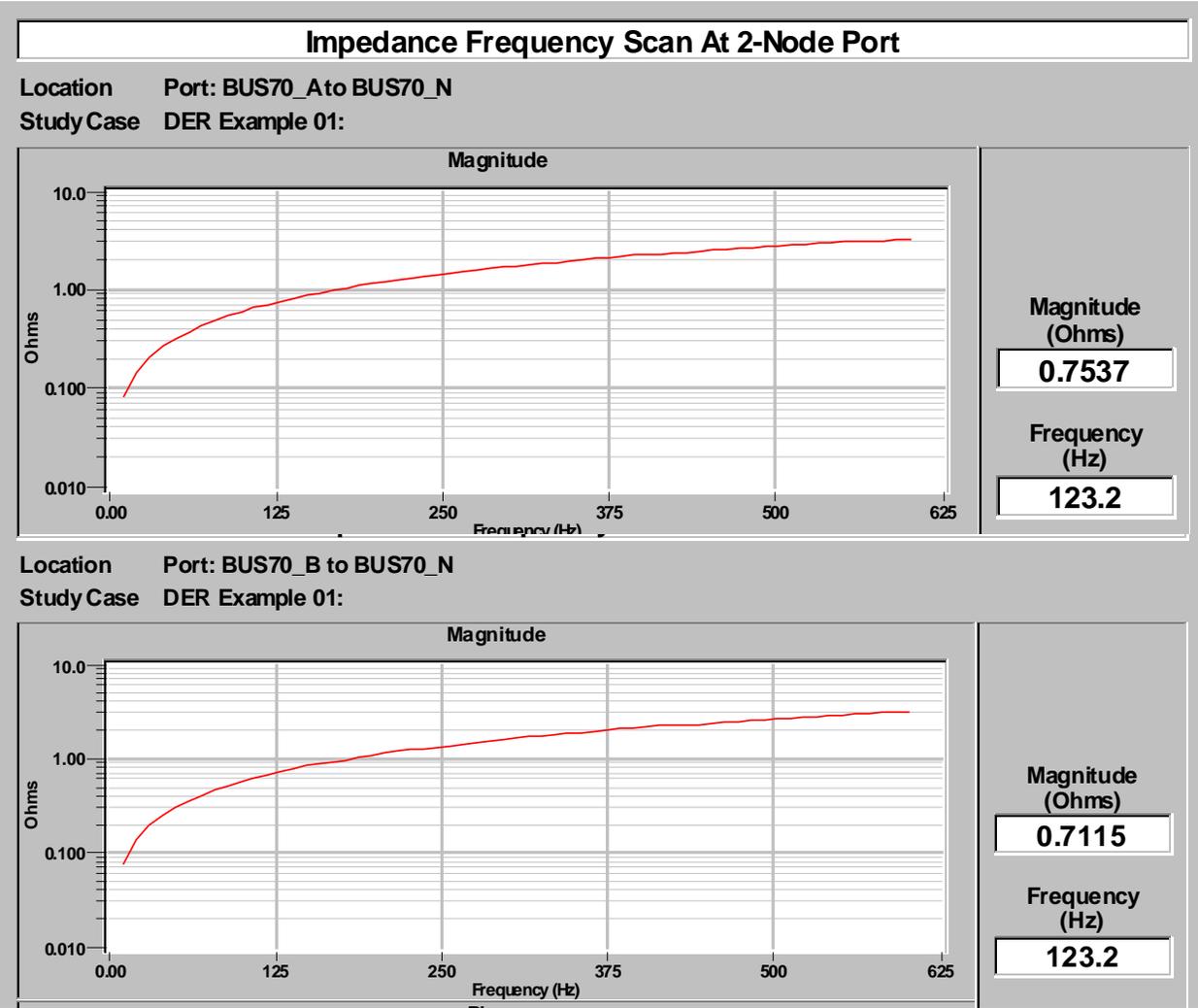


Figure B.10 Frequency Scans of Phases A and B for a Typical Customer System

Network-Converter Interactions

DER interface with the customer system using inverters. Each inverter takes feedback from the AC side by monitoring of voltage zero crossing. More sophisticated inverter controls may monitor the positive-sequence voltage at the interface bus to provide a reference. In both cases, imbalance in the voltage that may result from circuit asymmetries or asymmetric electrical loads will lead to imperfect operation of the inverter because of a small shift in the reference. This condition has been shown to generate additional distortion to the voltage waveform. Use of pulse width modulation can minimize the effects of network-converter interactions. In a MicroGrid, a relatively large number of converters could be connected to the customers’ systems. In this case, there may be interaction among the controls of the various converters and amplification of the ensuing dynamics. This issue needs further research.

Harmonic Resonance

The power electronics of a typical microsource will generate some harmonics. In addition, customer loads may disturb waveforms and thus generate harmonics. Because circuits may include inductance and capacitance, resonance is possible. When the resonance frequency coincides with a harmonic frequency, any injection of harmonics at this frequency will be amplified somewhere in the system. The severity of the condition can be determined by the value of the resonance Q ; the larger the Q value, the more severe the amplification will be. Q can be computed with frequency scans (Bode plots). Figure B2.11 illustrates an example system. The frequency scan at phase A of BUS70 is shown in Figure B2.12. Strong resonance can be seen at around 335 and 430 Hz. Q can be determined from this figure.

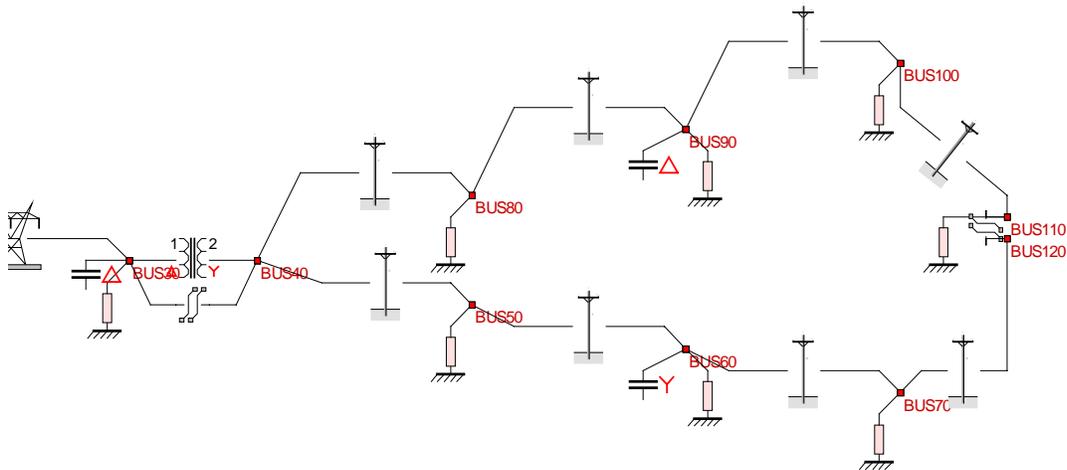


Figure B2.11 A Typical Customer System

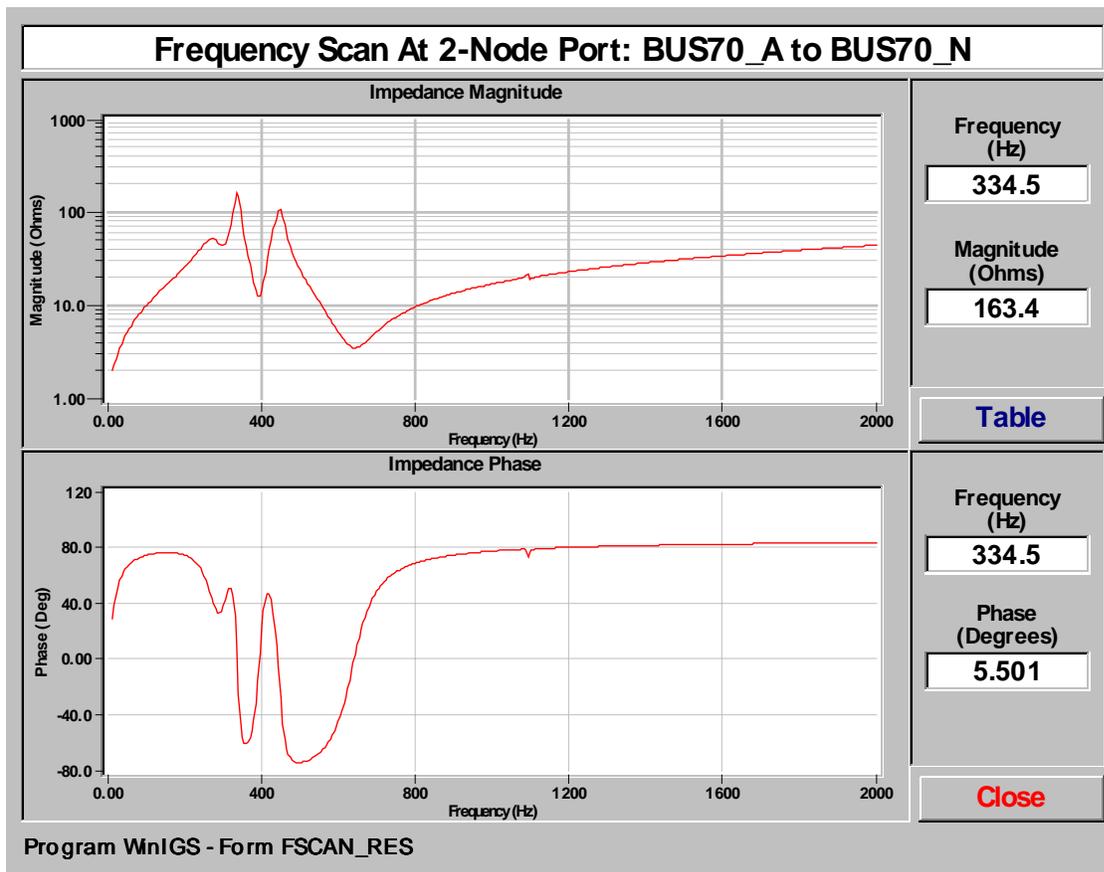


Figure B2.12 Frequency Scan at BUS70 of the System of Figure B2.11

B2.4 Voltage Drop, Reactive Power Demands, Circuit Losses, and Induction Machines

This section addresses voltage drop, reactive power, circuit losses and specific requirements of induction motors on a conventional distribution circuit. Industry practices to minimize voltage drops, improve power factors, and minimize losses are described. The impact of DER and possible ways that DER can be used to improve the performance of the distribution system with respect to these issues are also discussed.

Secondary distribution systems operate at the two standard voltages, 480 and 208 (line to line). At these voltages, the currents for typical loads are relatively high, so the voltage drop along the circuits is relatively high as compared to the nominal voltage.

Voltage Profile

The voltage profile of a customer system depends on the wire size, circuit length, and load distribution. Typical customer systems have circuits with relatively short lengths to minimize the voltage drop along each and therefore improve the voltage profile. Network systems have better voltage profile performance.

Effects of DER

The presence of DER can benefit a system’s voltage profile especially if the DER are placed at strategic locations. DER affect voltage profile in two ways: by modulating the loading of the circuit (i.e., the current level in the circuit is decreased if a microsource is placed at the appropriate location) and by injecting reactive power that can boost or control the voltage magnitude, just as a capacitor is used to increase the voltage magnitude in an AC circuit.

Three figures below illustrate the effects of a microsource on a system’s voltage profile. Figure B2.13 shows the voltage profile of a typical customer system. Figure B2.14 illustrates the same system’s voltage profile when a microsource is added at a specific location; it is assumed that the microsource is operated at unity power factor. Figure B2.15 illustrates the same configuration as the previous figure but with the microsource operated at 0.90 power factor current leading. Note that the system voltage profile of the system improves in each succeeding figure. The operation of the distributed energy resource at unity factor improves the voltage drop from 0.4 kV to 0.3 kV, a 25 percent improvement. The same microsource operated at 0.90 power factor (current leading) with all other system details remaining the same improves the voltage drop from 0.4 kV to 0.19 kV, a 53 percent improvement.

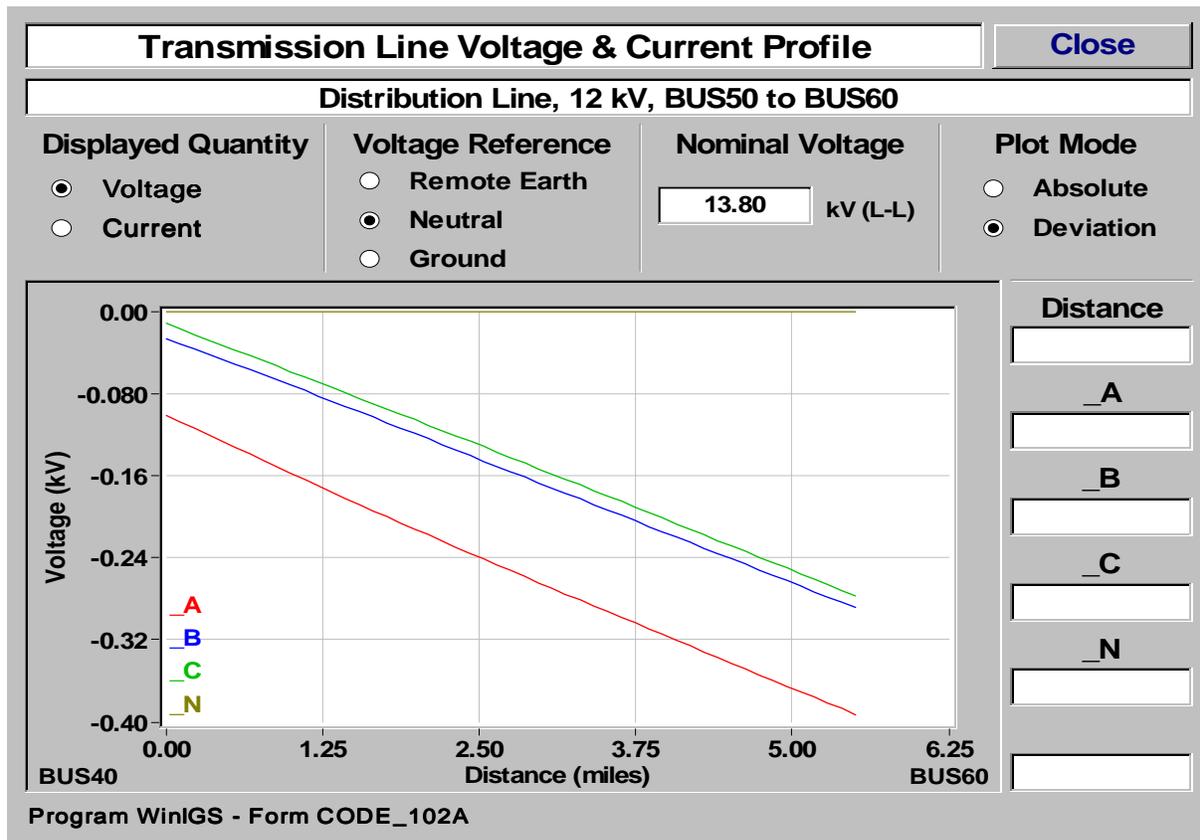


Figure B2.13. Voltage Profile of a Typical Customer System

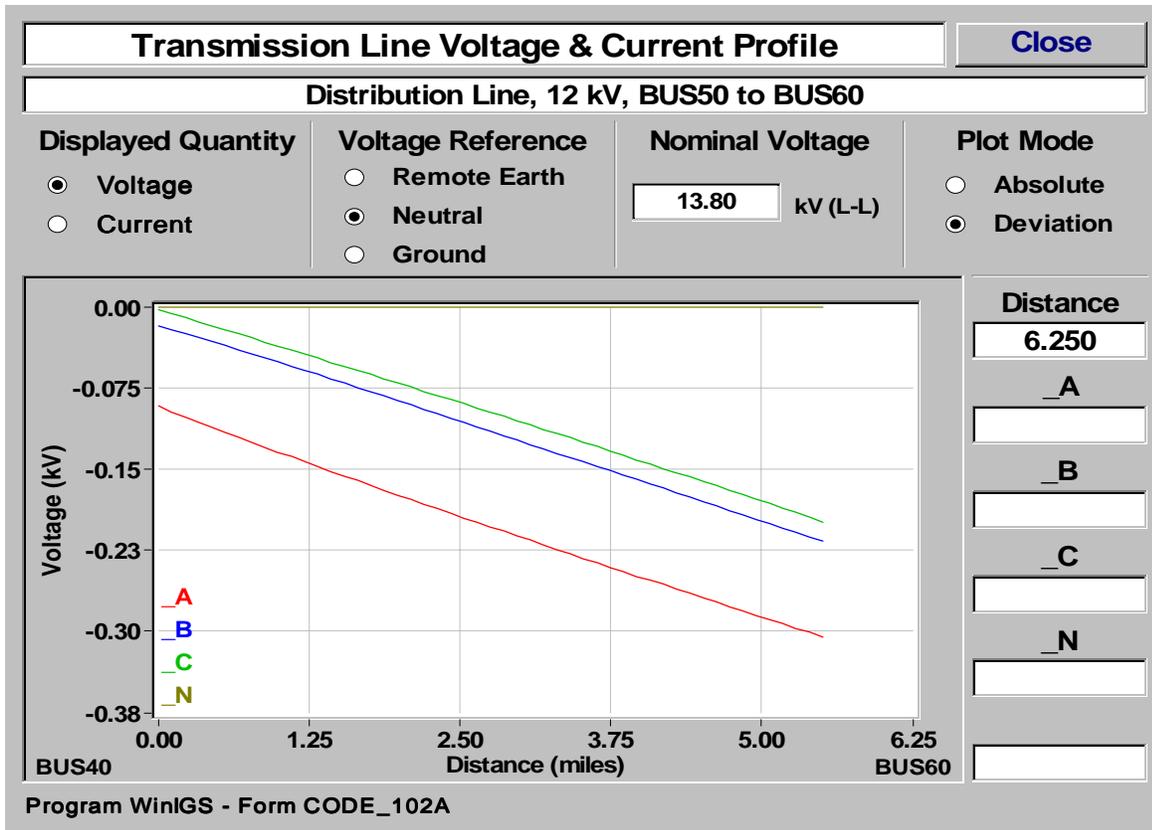


Figure B2.14. Voltage Profile of a Typical Customer System with One Microsource Operated at Unity Power Factor

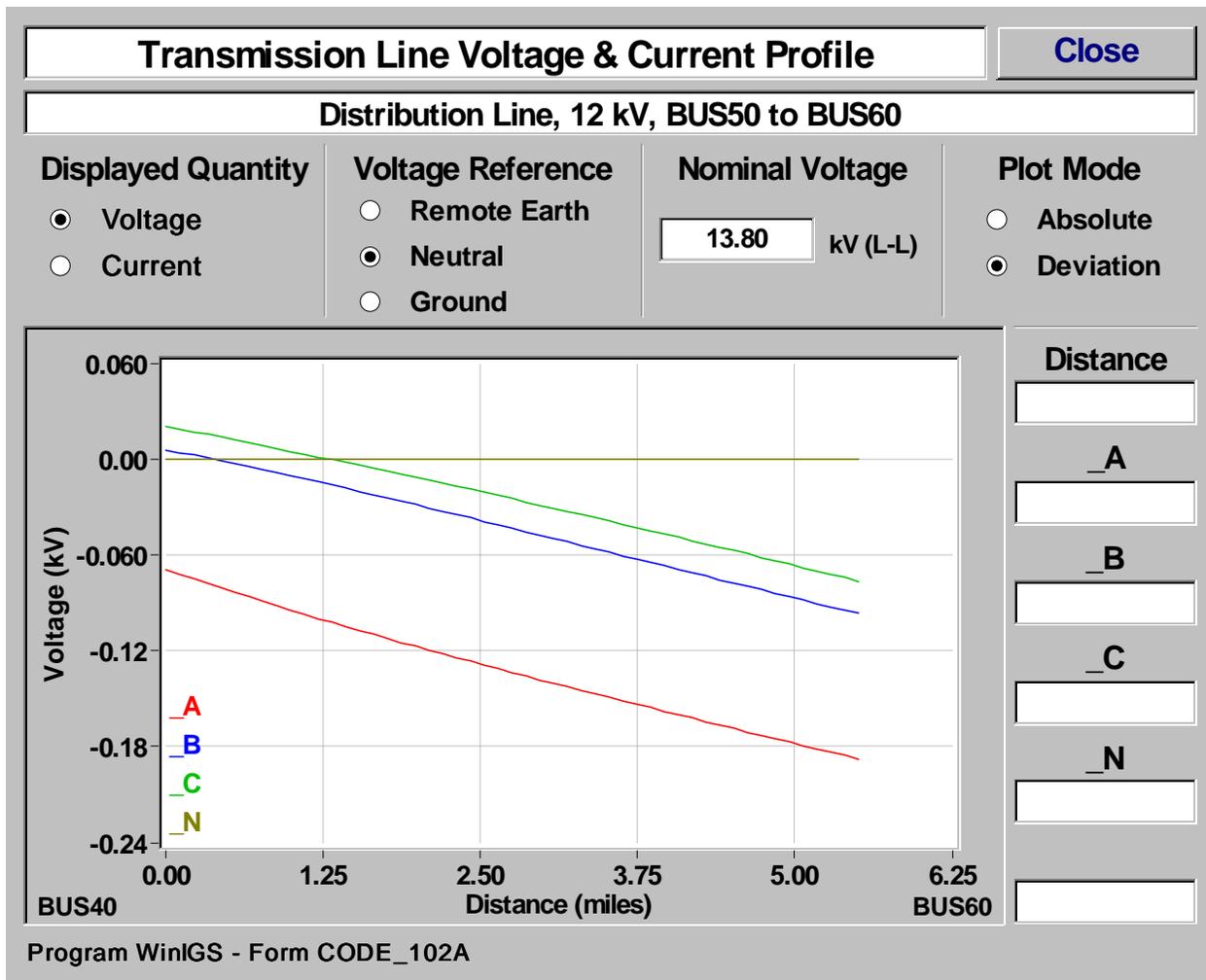


Figure B2.15. Voltage Profile in a Typical Customer System with One Microsource Operated at 0.95 (Current Leading) Power Factor

B2.5 Electromagnetic Interference

This section discusses electromagnetic fields (EMFs) in typical distribution systems and the factors that affect EMF levels. Specific system arrangements that may lead to increased EMFs and interference are described along with traditional methods and possible uses of DER to mitigate EMFs.

Any circuit that carries electric current will generate a magnetic and electric field. The effects of EMFs on humans have been controversial. The IEEE has taken the position that “prudent avoidance” is appropriate for EMFs. It is undeniable that the effect of EMFs on the performance of electrical equipment is often undesirable. For example, EMFs may cause CRT displays to flicker, interfere with the operation of pacemakers, and affect the current distribution in other circuits, leading to local overheating. These effects can be addressed as pure engineering problems. The possibility of MicroGrids offers an opportunity to rethink these issues and to establish good engineering practices for MicroGrid design.

EMF Sources

Electrical field sources are the voltages of the various conductors on circuits. Magnetic field sources are the electric currents that flow in the various conductors on circuits. Because of low operating voltage, the electric fields are low and are not considered to be significant. Electric currents are high and have the potential of generating high magnetic fields with undesirable effects.

EMFs in MicroGrids are illustrated in the figures below. A simplified customer system is shown in Figure B2.16: The system consists of two identical 208-V (line-to-line) circuits; one circuit is enclosed in aluminum conduit and the other in steel conduit of same nominal diameter. Figures B2.17 and B2.18 illustrate the magnetic field around each of the circuits at the same distance from the circuit center. Note that the magnetic field around the circuit enclosed in steel conduit is much lower (peak value of 76 milligauss) than the magnetic field around the circuit enclosed in the aluminum conduit (peak value of 365 milligauss).

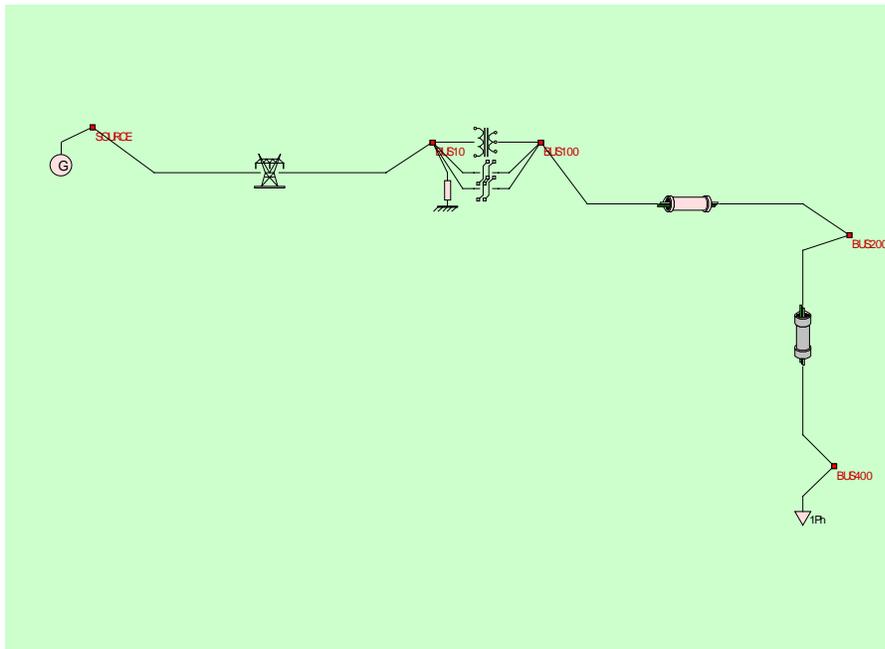


Figure B2.16 Illustration of a Distribution System in Steel and Aluminum Conduits

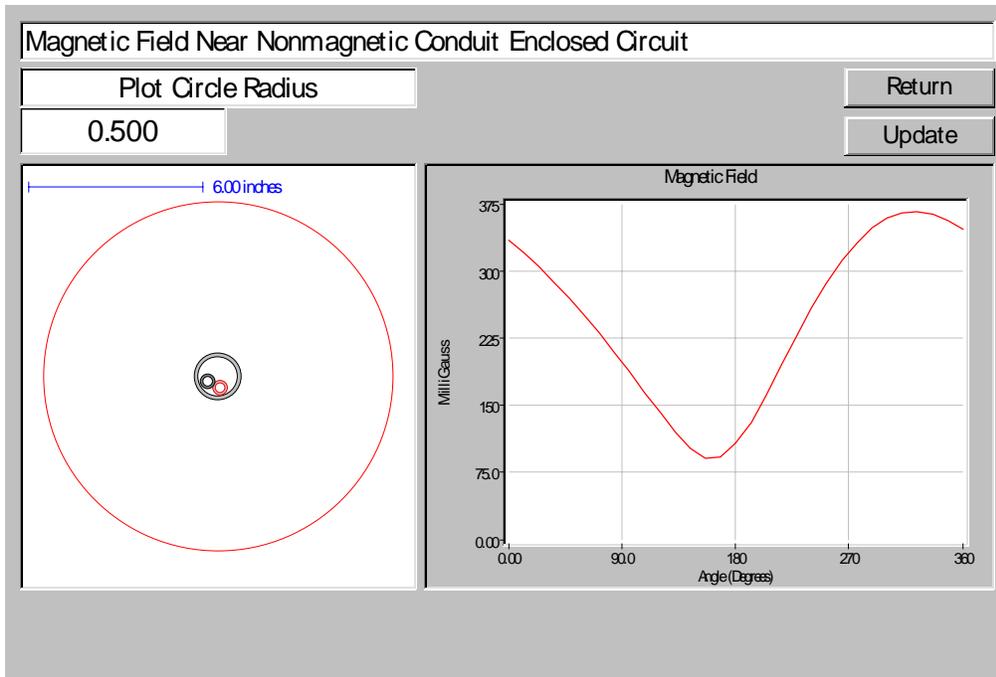


Figure B2.17 Illustration of the Magnetic Field Around the Circuit of Figure B2.16 Enclosed in Aluminum Conduit

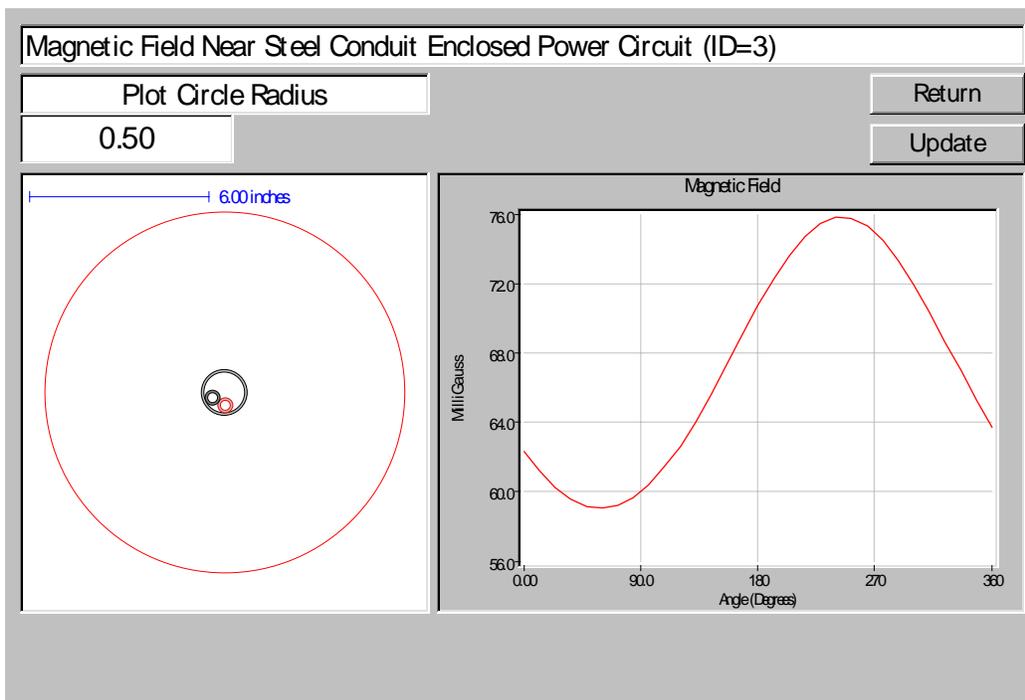


Figure B2.18 Illustration of the Magnetic Field Around the Circuit of Figure B2.16 Enclosed in Steel Conduit

Effects of DER on EMFs

Electromagnetic fields exist in any electric power distribution circuit. The level of the EMFs depends on the imbalance of the system and the geometry of the circuit conductors. The geometry of the circuit conductors can be controlled by the use of conduit that tends to put all the conductors close together so that the magnetic fields are minimized. The beneficial effects of DER can come from use of converter controls to minimize circuit imbalances.

APPENDIX C. Environmental Issues Related to MicroGrids

Although moving power generation closer to load creates opportunities for economic gain through higher reliability and use of waste heat, it raises serious environmental concerns. Moving power generation from large, easily monitored, and (usually) remote generating stations to smaller scale, difficult-to-monitor generation sites close to population concentrations is likely to increase human exposure to pollutants and noise. Other drawbacks are the dangers inherent in combustion at high pressures close to occupied spaces, and the problems of delivery and installation of equipment in occupied buildings.

The technologies that may be used in MicroGrids have diverse environmental characteristics. Some, notably PV systems, will have few environmental impacts at the point of generation; others, particularly diesel reciprocating engine generators, which are already numerous, can be quite damaging to the environment.

Air Quality

Given the serious air quality problems in many urban areas of the U.S., the prospect of thousands or hundreds of thousands of DER; particularly combustion devices, being installed in densely populated areas is cause for concern. High levels of ozone, particulate matter less than μm in diameter (PM-10), and carbon monoxide (CO) are among the largest contributors to current U.S. air quality problems. This section summarizes the impacts that MicroGrid technologies are likely to have on air quality.

Ozone levels are directly linked to ozone's precursor pollutants, reactive organic gas (ROG) and nitrogen oxide (NO_x). Nationally, the two largest source categories for volatile organic compound (VOC) emissions are industrial processes and transportation. NO_x emissions are mainly a consequence of combustion processes. Some fuels, notably coal, contain nitrogen that is oxidized during combustion. However even fuels that contain no nitrogen emit NO_x because it is formed from nitrogen and oxygen in the air in systems with high combustion temperatures. Nationally, the two biggest sources of NO_x are electric power generating plants and highway vehicles. Gas turbines, reciprocating engines, and reformers all involve high temperatures that result in NO_x production. Microturbines and fuel cells have much lower NO_x emissions because of their lower combustion temperatures.

Ozone tends to peak in late spring and into summer as temperatures warm. Because of lengthy reaction times, peak ozone concentrations frequently occur significantly downwind of source areas. Ozone tends to concentrate in densely populated areas, so high levels can occur at considerable distances downwind of urban centers. Overexposure to high levels of ozone can result in shortness of breath and other respiratory problems, including aggravated asthma symptoms, chest pain, coughing, and possible chronic lung damage. It is therefore important to focus on ozone characteristics in considering the effects of DER systems.

PM-10 consists primarily of soot, dust, smoke, fumes, or mists and is a growing health concern. Major sources of PM-10 include motor vehicles, wood-burning stoves and fireplaces, construction, landfills, agriculture, wind fires, windblown soil, and industrial sources. Under

EPA legislation, the 24-hour PM-10 standard is a maximum concentration of 150 $\mu\text{g}/\text{m}^3$. PM-10 dominates in summer and fall as a result of arid soils that winds and agricultural activity stir into the ambient air. Enhanced levels of particulate matter can bring on asthma attacks and bronchitis and can cause premature death in people with cardiac or respiratory disease. Among DER technologies, diesel reciprocating engines raise the largest PM-10 concern; microturbines and fuel cell generate minimal levels of PM-10.

Carbon monoxide (CO) is the result of incomplete fuel combustion. It is a byproduct of motor vehicle exhaust, which contributes more than two-thirds of all CO emissions in the U.S. In general, CO emissions in the U.S. are considerably less severe than ozone or PM concentrations. Because CO originates mainly from automobile exhaust, improved regulations leading to cleaner burning fuels have significantly reduced CO emissions. High levels of carbon monoxide exposure are believed to affect the central and nervous system, depriving the body of oxygen and potentially contributing to cardiovascular disease. CO can result from all combustion processes, but controlled lean combustion used for power generation does not usually produce CO unless equipment is malfunctioning. However, because DER equipment might well be running in enclosed spaces that might result in CO buildup, CO risks must be taken seriously in MicroGrid planning and design.

Environmental Impacts Estimate for a Microturbine

Below are rough estimates of emissions from a small, newly installed microturbine. Calculations are based on the characteristics of a 30-kW Capstone microturbine.

Technical specifications for this product estimate NO_x emissions of approximately 6.7 g/hr or 58.7 kg/yr if the generator runs year round at an output of 28 kW generating 245 MWh), which translates to 0.24 G/kWh. This figure corresponds to an exhaust gas concentration of less than 9 ppmv, comparable a small amount more than the emissions of three cars in the state of California in 2000. This emissions rate is comparable to that of central station generation. The estimated amount of CO emitted from a microturbine is just over 100 kg/yr, which is equivalent to only a fraction of one car.

Reducing pollutants from combustion technologies

Modifications to reduce pollutant emissions from reciprocating engines include incorporating: precise controls for air-to-fuel ratios, lean-burn combustion techniques, electronic ignition, exhaust gas recirculation, wet controls, and fuel conditioning. Combustion modifications for gas turbines include incorporating wet controls, lean pre-mix, and catalytic converters. Common drawbacks of these modifications are increased cost, reduced efficiency, and a potential increase in emissions of other pollutants.

Post-combustion technologies for engines and turbines include selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR). For engines, catalytic converters and oxidation catalysts are used to eliminate pollution emissions. Diesel engines may use particulate traps, oxidation catalysts, NO_x absorbers, and lean-NO_x catalytic converters to clean emissions. Technologies are currently being developed that substantially reduce NO_x and CO emissions

from gas turbines; however, further efforts are needed to bring these technologies from the demonstration phase to commercial production.

Table C.1 shows estimates of emission rates for common existing distributed generating technologies and for technologies likely to be developed during the next decade.

Present-Day Air Emissions Factors (g/kWh)

	NOx	CO	PM
Fuel Cell			
250 kW	N/A	N/A	N/A
Microturbine			
75 kW	0.24	0.24	N/A
Diesel Back-up			
7.5 kW	8.17	3.26	0.54
500 kW	8.57	0.54	0.16
Gas Back-up			
55 kW	6.05	N/A	N/A
500 kW	25.29	5.66	N/A

Table C.1. DER Technology Emissions Rates in g/kWh

As Table C.1 shows, current estimates of emissions rates vary widely, but it is clear that the technologies incorporated in a MicroGrid will have a significant impact on MicroGrid emissions. A key public policy question is how to encourage use of technologies with fewer environmental consequences. The emissions rates shown are for uncontrolled equipment; the environmental performance of MicroGrids can be considerably improved through application of the various emissions control technologies noted above, which will likely be required in many jurisdictions. The control technologies appropriate for reducing emissions, e.g. catalytic converters, are familiar and well developed for mobile applications, so there are no significant technical barriers to their deployment in MicroGrids. The regulatory situation, however, is more complex, as described below.

Air Pollutant Transport

In areas with serious air quality problems, air transport from one region to another is an important environmental issue. Pollutant transport from the San Francisco Bay Area to the Central Valley is an example that shows the importance of considering air quality conditions and flow patterns from adjoining air basins. A 1990 study by the California Air Resources Board (ARB) investigated ozone and ozone precursor transport to the Central Valley in California. The 1983-1986 assessment concluded that approximately 43 percent of ozone exceedance days in California's central valley were significantly affected by upstream wind flow patterns from the San Francisco area .

Air Pollution Regulations and DER

The federal government, through the EPA, sets pollution standards and oversees state and local behavior, enforcing programs related to motor vehicle emissions, fuels, and smog checks. State or local air quality authorities develop and implement control measures for stationary sources such as factories and plants. Regulations for generator sources focus mainly on larger scale operations, but DER are considered point sources and are accordingly subject to regulation by the appropriate authority. In many jurisdictions, permit conditions for currently assume that small-scale generators will only be used in emergencies, so permit conditions are written accordingly. The prospect of regulating distributed generation technologies is complex because regulatory agencies that control emissions within each air district are concerned with improving air quality within their own regions. Displacing larger generators from the grid and replacing them with local generators will influence air quality in many localities, so there could be resistance from local air quality agencies. The possible increased local emissions resulting from a nearby DER source would likely be considered problematic by the local agency despite the tradeoff of potential reduced emissions outside the local area.

Surveys of DER installation sites have found that the most challenging aspects of the siting and permitting process were the paperwork, regulatory interpretation process, and annual testing procedures involved with obtaining an air pollution permit. The most costly aspects of environmental controls were on-site testing (if required) along with legal and engineering fees. The permit process should be standardized to make it less time consuming. The process could be streamlined if certain equipment could be pre-qualified as meeting an acceptable minimum standard.

Noise

Noise pollution is primarily an issue associated with road, highway, or building construction; industrial processes; airplanes; and vehicles in heavily traveled areas. As a result, regulations tend to focus on industrial and traffic noise.

Some example typical noise levels are 50 dBA for quiet urban daytime, 25 dBA for a quiet rural nighttime, 60 dBA for heavy traffic at a distance of 90 m, and nearly 100 dBA for a gas lawn mover at 1m.

Some states that regulate noise levels from industrial operations are Oregon, Hawaii, Delaware, and Maryland. In Oregon, the maximum allowable noise level for industrial sources is 60 dBA. Hawaii, Minnesota, and Maryland all have a maximum permissible sound level of 70 dBA for industrial activities, and New Jersey and Delaware cap these noise levels at 65 dBA.

The Federal Highway Administration Regulations constitute the Federal Noise Standard, which states that noise abatement measures must be taken when noise levels for highway construction approach or exceed the Noise Abatement Criteria (NAC). The NAC for residences, motels, hotels, schools, churches, hospitals, and libraries specify a maximum interior level of 52 dBA. For comparable exterior situations, the NAC level is 67 dBA. For quiet lands whose serenity and low noise level are considered essential, the NAC level is 57 dB.

A 25- to 30-kW microturbine installation produces an approximate noise level of 65 dBA at 10 m. Noise level increases/decreases by approximately 6 dBA for each halving/doubling of

distance away from the sound source. This means that a properly functioning microturbine could, theoretically, be heard up to a distance of more than 10 km. Realistically, however, this noise would not carry such a great distance under normal outdoor conditions. Using the rule of thumb, sound levels would be about 53 dBA 40 m away from the source and only 35 dBA 320 m away. This 35 dBA is almost comparable to the noise level in a quiet nighttime rural location, virtually unnoticeable for outdoor conditions. This example indicates that noise concerns can easily be avoided when DER are deployed.

Conclusions

The environmental issues raised by DER are significant and need to be addressed. Regulations or incentives should be created to encourage adoption of the more environmentally benign DER technologies. With local air pollution control districts focused primarily on air quality conditions within their jurisdictions, adoption of DER could be stymied by local concerns even though a DER installation might be less polluting than the central station energy production that it displaces, reducing emissions overall in the wider geographic area served by the central station. In addition, the local/regional effects of smog on dense populations suggest that total human exposure could be worse with DER in place even if total emissions are lowered.

All of the possible environmental impacts of DER can be mitigated to some extent. Air emissions can be reduced by choosing low-emission technologies, limiting hours of operation, modifying combustion, or incorporating post-combustion treatment. Noise and vibration problems can be addressed by installing generation equipment on shock-isolated pads and in enclosures. Silencing equipment for exhaust is available for turbines and engines. In general, noise abatement techniques have worked for microsources, and noise has not caused siting problems in residential and commercial areas, but wider deployment of DER could result in stronger opposition from neighbors .

With the increased interest in distributed generation resources, the current regulatory status for DER deployment is changing quickly and the need to address environmental issues is becoming more critical in establishing a context of a controlled DER environment.