A Look at Microgrid Technologies and Testing Projects from Around the World

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Making Microgrids Work

DISTRIBUTED ENERGY RESOURCES (DER), INCLUDING DISTRIBUTED GENERATION (DG) and distributed storage (DS), are sources of energy located near local loads and can provide a variety of benefits including improved reliability if they are properly operated in the electrical distribution system. Microgrids are systems that have at least one distributed energy resource and associated loads and can form intentional islands in the electrical distribution systems. Within microgrids, loads and energy sources can be disconnected from and reconnected to the area or local electric power system with minimal disruption to the local loads. Any time a microgrid is implemented in an electrical distribution system, it needs to be well planned to avoid causing problems.

For microgrids to work properly, an upstream switch must open (typically during an unacceptable power quality condition), and the DER must be able to carry the load on the islanded section. This includes maintaining suitable voltage and frequency levels for all islanded loads. Depending on switch technology, momentary interruptions may occur during transfer from grid-connected to islanded mode. In this case, the DER assigned to carry the island loads should be able to restart and pick up the island load after the switch has opened. Power flow analysis of island scenarios should be performed to insure that proper voltage regulation is maintained and to establish that the DER can handle inrush during "starting" of the island. The DER must be able to supply the real and reactive power requirements during islanded operation and to sense if a fault current has occurred downstream of the switch location. When power is restored on the utility side, the switch must not close unless the utility and "island" are synchronized. This requires measuring the voltage on both sides of the switch to allow synchronizing the island and the utility.

Microgrids' largest impact will be in providing higher reliability electric service and better power quality to the end customers. Microgrids can also provide additional benefits to the local utility by providing dispatchable power for use during peak power conditions and alleviating or postponing distribution system upgrades.

Microgrid Technologies

Microgrids consist of several basic technologies for operation. These include DG, DS, interconnection switches, and control systems. One of the technical challenges is the design, acceptance, and availability of low-cost technologies for installing and using microgrids. Several technologies are under development to allow the safe interconnection and use of microgrids (see Figure 1).

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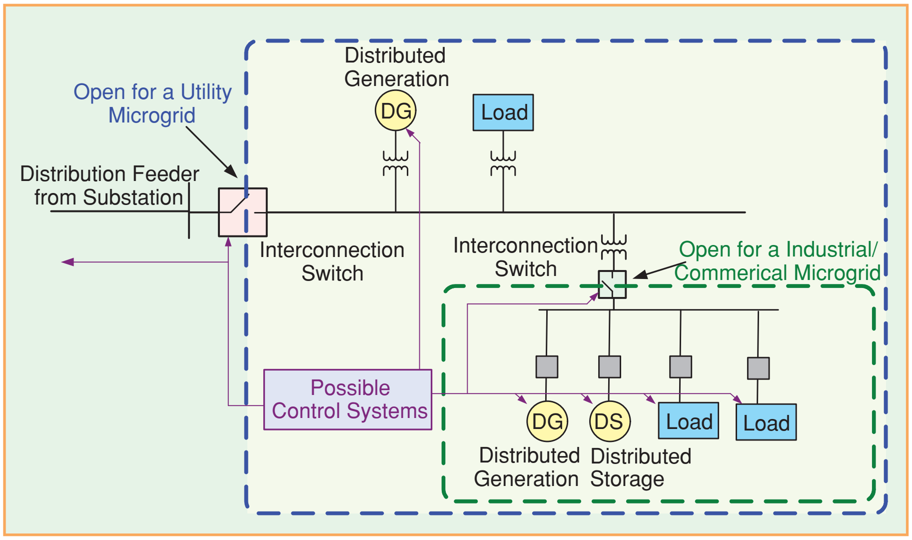


figure 1. Microgrids and components.

Distributed Generation

DG units are small sources of energy located at or near the point of use. DG technologies (Figures 2–5) typically include photovoltaic (PV), wind, fuel cells, microturbines, and reciprocating internal combustion engines with generators. These systems may be powered by either fossil or renewable fuels.

figure 2. Microturbines with heat recovery.

Some types of DG can also provide combined heat and power by recovering some of the waste heat generated by the source such as the microturbine in Figure 2. This can significantly increase the efficiency of the DG unit. Most of the DG technologies require a power electronics interface in order to convert the energy into grid-compatible ac power. The power electronics interface contains the necessary circuitry to convert power from one form to another. These converters may include both a rectifier and an inverter or just an inverter. The converter is compatible in voltage and frequency with the electric power system to which it will be connected and contains the necessary output filters. The power electronics interface can also contain protective functions for both the distributed energy system and the local electric power system that allow paralleling and disconnection from the electric power system. These power electronic interfaces provide a unique capability to the DG units and can enhance the operations of a microgrid.

Distributed Storage

DS technologies are used in microgrid applications where the generation and loads of the microgrid cannot be exactly matched. Distributed storage provides a bridge in meeting the power and energy requirements of the microgrid. Storage capacity is defined in terms of the time that the nominal energy capacity can cover the load at rated power. Storage capacity can be then categorized in terms of energy density requirements (for medium- and long-term needs) or in terms of power density requirements (for short- and very short-term needs). Distributed storage enhances the overall performance of microgrid systems in three ways. First, it stabilizes and permits DG units to run at a constant and stable output, despite load fluctuations. Second, it provides the ride-through capability when there are dynamic variations of primary energy (such as those of sun, wind, and hydropower sources). Third, it permits DG to seamlessly operate as a dispatchable unit. Moreover, energy storage can benefit power systems by damping peak surges in electricity demand, countering momentary power disturbances, providing outage ride-through while backup generators respond, and reserving energy for future demand.

There are several forms of energy storage available that can be used in microgrids; these include batteries, supercapacitors, and flywheels. Battery systems store electrical energy in the form of chemical energy (Figure 6). Batteries are dc power systems that

figure 3. Wind turbine.

require power electronics to convert the energy to and from ac power. Many utility connections for batteries have bi-directional converters, which allow energy to be stored and taken from the batteries. Supercapacitors, also known as ultracapacitors, are electrical energy storage devices that offer high power density and extremely high cycling capability. Flywheel systems have recently regained consideration as a viable means of supporting critical load during grid power interruption because of their fast response compared to electrochemical energy storage. Advances in power electronics and digitally controlled fields have led to better flywheel designs that deliver a cost-effective alternative in the power quality market. Typically, an electric motor supplies mechanical energy to the flywheel and a generator is coupled on the same shaft that outputs the energy, when needed, through a converter. It is also possible to design a bi-directional system with one machine that is capable of motoring and regenerating operations.

Interconnection Switch

The interconnection switch (Figure 7) ties the point of connection between the microgrid and the rest of the distribution system. New technology in this area consolidates the various power and switching functions (e.g., power switching, protective relaying, metering, and communications) traditionally provided by relays, hardware, and other components at the utility interface into a single system with a digital signal processor (DSP). Grid conditions are measured both on the utility and microgrid sides of the switch through current transformers (CTs) and potential transformers (PTs) to determine operational conditions (Figure 8). The interconnection switches are designed to meet grid interconnection standards (IEEE 1547 and UL 1741 for North America) to minimize custom engineering and site-specific approval processes and lower cost. To maximize applicability and functionality, the controls are also designed to be technology neutral and can be used with a circuit breaker as well as faster semiconductor-based static switches like thyristors and integrated gate bipolar transistor technologies and are applicable to a variety of DG assets with conventional generators or power converters.

Control Systems

The control system of a microgrid is designed to safely operate the system in grid-connected and stand-alone modes. This system may be based on a central controller or imbedded as autonomous parts of each distributed generator. When the utility is disconnected the control system must control the local voltage and frequency, provide (or absorb) the instantaneous real power difference between generation and loads, provide the difference between generated reactive power and the actual reactive power consumed by the load; and protect the internal microgrid.

In stand-alone mode, frequency control is a challenging problem. The frequency response of larger systems is based on rotating masses and these are regarded as essential for the inherent stability of these systems. In contrast, microgrids are inherently converter-dominated grids without or with

figure 4. Fuel cell.

figure 5. PV array.

figure 6. Large lead-acid battery bank.

figure 7. Interconnection switch and control board.

very little directly connected rotating masses, like flywheel energy storage coupled through a converter. Since microturbines and fuel cells have slow response to control signals and are inertia-less, isolated operation is technically demanding and raises load-tracking problems. The converter control systems must be adapted to provide the response previously obtained from directly connected rotating masses. The frequency control strategy should exploit, in a cooperative way, the capabilities of the micro sources to change their active power, through frequency control droops, the response of the storage devices, and load shedding.

Appropriate voltage regulation is necessary for local reliability and stability. Without effective local voltage control, systems with high penetration of distributed energy resources are likely to experience voltage and/or reactive power excursions and oscillations. Voltage control requires that there are no large circulating reactive currents between sources. Since the voltage control is inherently a local problem, voltage regulation faces the same problems in both modes of operation; i.e., isolated or interconnected. In the grid-interconnected mode, it is conceivable to consider that DG units can provide ancillary services in the form of local voltage support. The capability of modern power electronic interfaces offers solutions to the provision of reactive power locally by the adoption of a voltage versus reactive current droop controller, similar to the droop controller for frequency control.

Microgrid Testing Experience

Around the world, there are several active experiments in the microgrid area covering an array of technologies. As part of this research, microgrid topologies and operational configurations are being defined and design criteria established for all possibilities of microgrid applications.

Testing Experience in the United States

Consortium for Electric Reliability Solutions (CERTS) Testbed

The objective of the CERTS microgrid testbed is to demonstrate a mature system approach that allows for high penetration of DER equipment by providing a resilient platform for plug-and-play operation, use of waste heat and intermittent sources, and enhancement of the robustness and reliability of the customers' electrical supply. The CERTS microgrid has two main components: a static switch and autonomous sources. The static switch has the ability to autonomously island the microgrid from disturbances such as faults, IEEE 1547 events, or power quality events. After islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. This synchronization is achieved by using the frequency difference between the islanded microgrid and the utility grid. Each source can seamlessly balance the power on the islanded microgrid using real power versus frequency droop and maintain voltage using the reactive power versus voltage droop. The coordination between sources is through frequency, and the voltage controller provides local stability. Without local voltage control, systems with high penetrations of DG could experience voltage and/or reactive power oscillations. Voltage control must also insure that there are no large circulating reactive currents between sources. This requires a voltage versus reactive power droop controller so that, as the reactive power generated by the source becomes more capacitive, the local voltage set point is reduced. Conversely, as reactive power becomes more inductive, the voltage set point is increased.

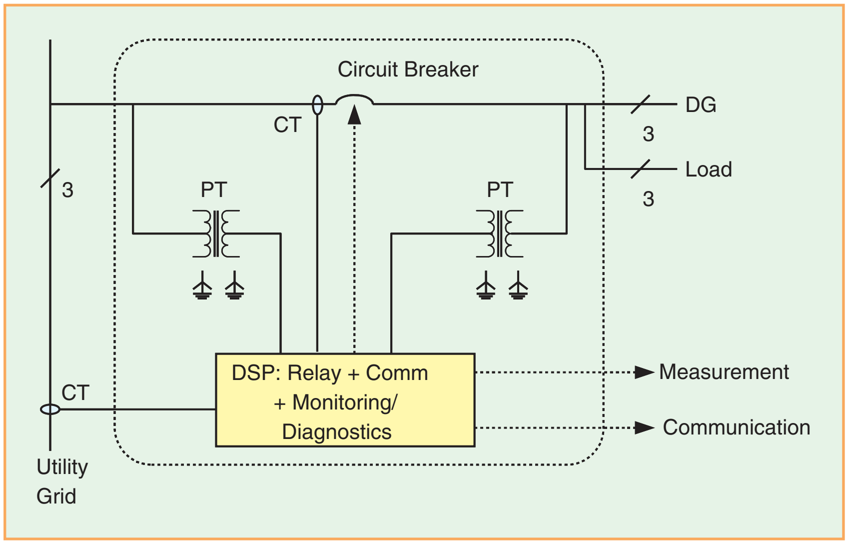


figure 8. Schematic diagram of a circuit breaker based interconnection switch.

The CERTS microgrid has no "master" controller or source. Each source is connected in a peer-to-peer fashion with a localized control scheme implemented with each component. This arrangement increases the reliability of the system in comparison to a master–slave or centralized control scheme. In the case of a master–slave architecture, the failure of the master controller could compromise the operation of the whole system. The CERTS testbed uses a central communication system to dispatch DG set points as needed to improve overall system operation. However, this communication network is not used for the dynamic operation of the microgrid. This plug-and-play approach allows expansion of the microgrid to meet the requirements of the site without extensive re-engineering.

The CERTS testbed (Figure 9) is located at American Electric Power's Walnut test site in Columbus, Ohio. It consists of three 60-kW converter based sources and a thyristor based static switch. The prime mover in this case is an automobile internal combustion engine converted to run on natural gas. It drives a synchronous generator at variable speeds to achieve maximum efficiencies over a wide range of loads. The output is rectified and inverted to insure a constant ac frequency at the microgrid. To insure that the converter can provide the necessary energy demanded by the CERTS controls there is storage on the dc bus. This also insures that the dynamics of the permanent magnet and generator are decoupled from the dynamics of the converter. This insures that a variety of energy sources can have the same dynamic response as the sources used at the testbed.

The testbed has three feeders, two of which have DG units connected and can be islanded. One of these feeders has two sources separated by 170 m of cable. The other feeder has a single source, which allows for testing parallel operation of sources. The third feeder stays connected to the utility but can receive power from the micro sources when the static switch is closed without injecting power into the utility. The objective of the testing is to demonstrate the system dynamics of each component of the CERTS microgrid. This includes smooth transitions from grid-connected to islanded operation and back, high power quality, system protection, speed of response of the sources, operation under difficult loads, and autonomous load tracking.

Figure 10 is an example of islanding dynamics between two sources on a single feeder at the CERTS testbed. Initially, the microgrid is utility connected with unit A and unit B output at 6 kW and 54 kW, respectively. The load is such that the grid provides 42 kW. Upon islanding, unit B exceeds 60 kW and quickly settles at its maximum steady-state operating point of 60 kW with a reduced frequency of 59.8 Hz due to the power versus frequency droop. Unit A increases to 42 kW and converges to the same islanded frequency. The smoothness and speed of the transition is seen in the invert currents and the microgrid voltages. The loads do not see the islanding event.

Figure 11 shows voltage across the switch and the phase currents through the static switch during autonomous

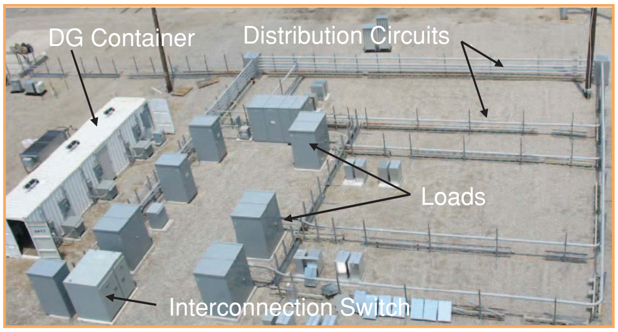
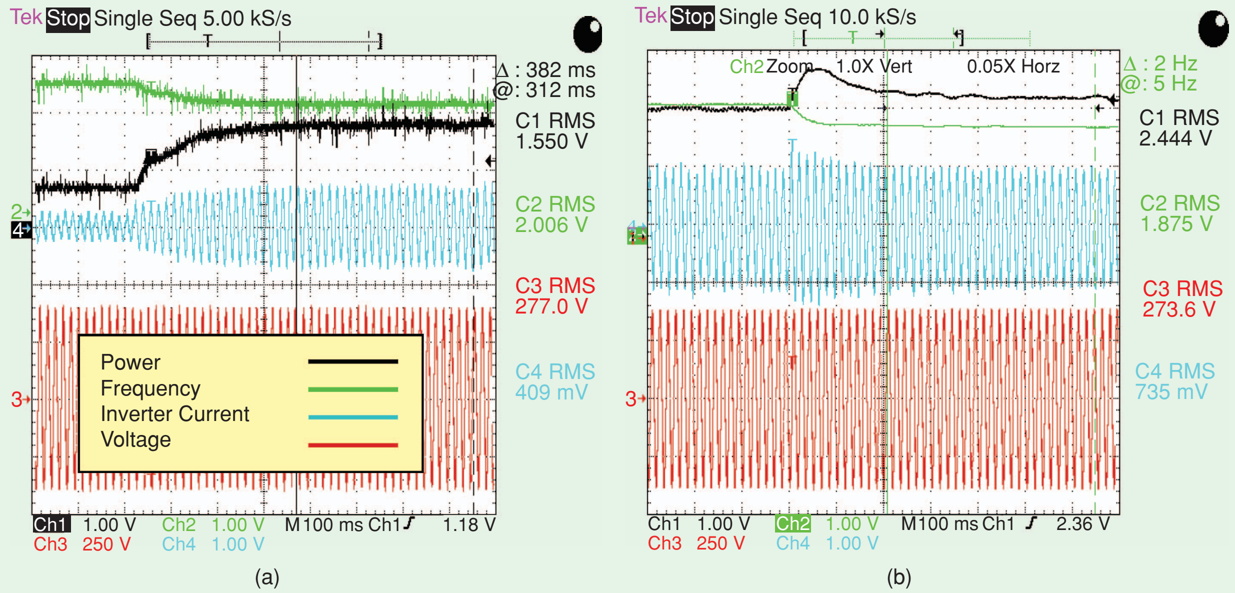


figure 9. CERTS/AEP microgrid testbed.



(a)

(b)

figure 10. Operation of two 60-kW sources using CERTS autonomous controls during an islanding event.

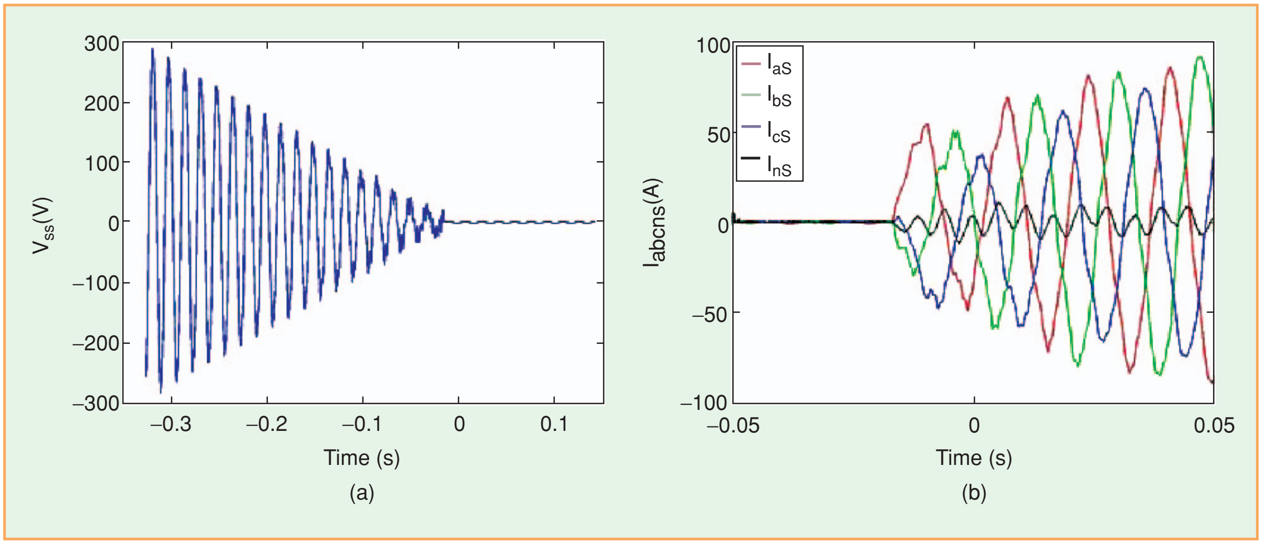


figure 11. Synchronization of the microgrid to the utility

synchronization. This synchronization is achieved by using the frequency difference between the islanded microgrid and the utility grid. This results in a low-frequency beat voltage across the switch. When the two voltages come in phase due to this frequency difference the switch will close. The phase currents display a smooth transition due to closing at zero voltage phase difference. The unbalanced currents are driven by a utility voltage unbalance of around 1% and a balanced voltage created by the DG source. All loads see balanced voltages provided by the DG sources. The neutral third harmonic current and phase current distortion are due to transformer magnetization currents.

The fundamental and third-harmonic frequency component from the transformer magnetization is apparent. As the loading of the transformer increases, the distortion becomes a smaller component of the total current.

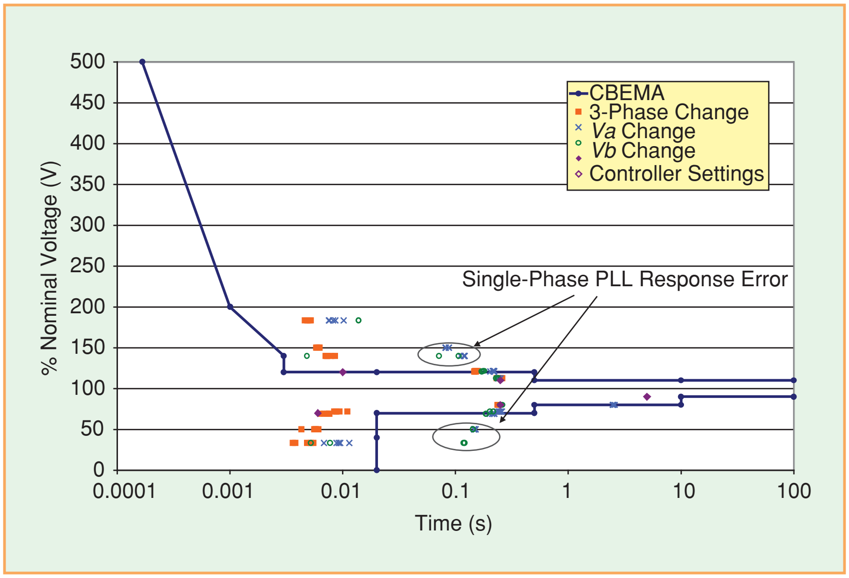


figure 12. Testing of a circuit breaker-based microgrid switch versus the ITI curve.

Interconnection Switch Testing

The National Renewable Energy Laboratory has worked with a variety of U.S. interconnection switch manufacturers on the development of advanced interconnection technologies that allow paralleling of distributed generators with the utility for uninterrupted electrical service and the ability to parallel and sell electricity back to the utility. This research promotes the development of new products and technologies that enable faster switching, greater reliability, and lower fault currents on the electrical grids, thereby providing fewer disruptions for customers while expanding capabilities as an energy-intensive world becomes more energy efficient in the future.

Testing of the various switch technologies includes typical protective relay function tests such as detection and tripping for over–and undervoltage, over- and underfrequency, phase sequence, reverse power, instantaneous overcurrent, and discrete event trip tests. To evaluate the switches' interconnection requirements, conformance tests to the IEEE 1547.1 standard are conducted. These tests evaluate if the unit detects and trips for over- and undervoltage, over- and underfrequency, synchronization, unintentional islanding, reconnection, and open-phase tests. To evaluate the power quality functions of the switch, tests are performed to verify that the switch responded as expected, which was to disconnect the grid and DG terminals when a power quality event occurred. Figure 12 shows results from the power quality testing done on a circuit-breaker-based switch. This testing showed that there is a minimum trip time for the breaker (0.005 s) and that the control logic for the breaker needs to be more accurately tuned to stay within the Information Technology Industry (ITI) Council curve.

Testing Experience in Japan

The New Energy and Industrial Technology Development Organization (NEDO) is currently supporting a variety of microgrid demonstration projects applying renewable and distributed generation. The first group of projects, called Regional Power Grids with Various New Energies, was implemented at three locations in Japan: Expo 2005 Aichi, recently moved to the Central Japan Airport City (Aichi project), Kyoto Eco-Energy project (Kyotango project), and Regional Power Grid with Renewable Energy Resources in Hachinohe City (Hachinohe project). In these three projects, control systems capable of matching energy demand and supply for microgrid operation were established. An important target in all of the projects is achieving a matched supply and demand of electricity. In each project, a standard for the margin of error between supplied energy and consumed energy over a certain period was set as a control target.

In the Aichi project, a power supply system utilizing fuel cells, PV, and a battery storage system, all equipped with converters, was constructed. A block diagram of the supply system for the project is shown in Figure 13. The fuel cells adopted for the system include two molten carbonate fuel cells (MCFCs) with capacities of 270 kW and 300 kW, one 25-kW solid oxide fuel cell (SOFC), and four 200-kW phosphoric acid fuel cells (PAFCs). The total capacity of the installed PV systems is 330 kW, and the adopted cell types include multicrystalline silicon, amorphous silicon, and a single crystalline silicon bifacial type. A sodium-sulfur (NaS) battery is used to store energy within the supply system and it plays an important role in matching supply and demand. In the Aichi project, the load-generation balancing has been maintained at 3% for as short as ten-minute intervals. The Aichi project experienced a second grid-independent operation mode in September 2007. In this operational mode, the NaS battery converter controls voltage and balancing of the load.

In the Kyotango project, the energy supply facilities and demand sites are connected to a utility grid and are integrated by a master control system. The energy supply system functions as a “virtual microgrid.” A management system for matching the demand and supply of electricity is being demonstrated and a reduction in imbalances to within 3% of expected demand for five-minute intervals was achieved. Several criteria related to power quality (outages, voltage fluctuations, and frequency fluctuations) are being monitored during the demonstration period to determine if the system

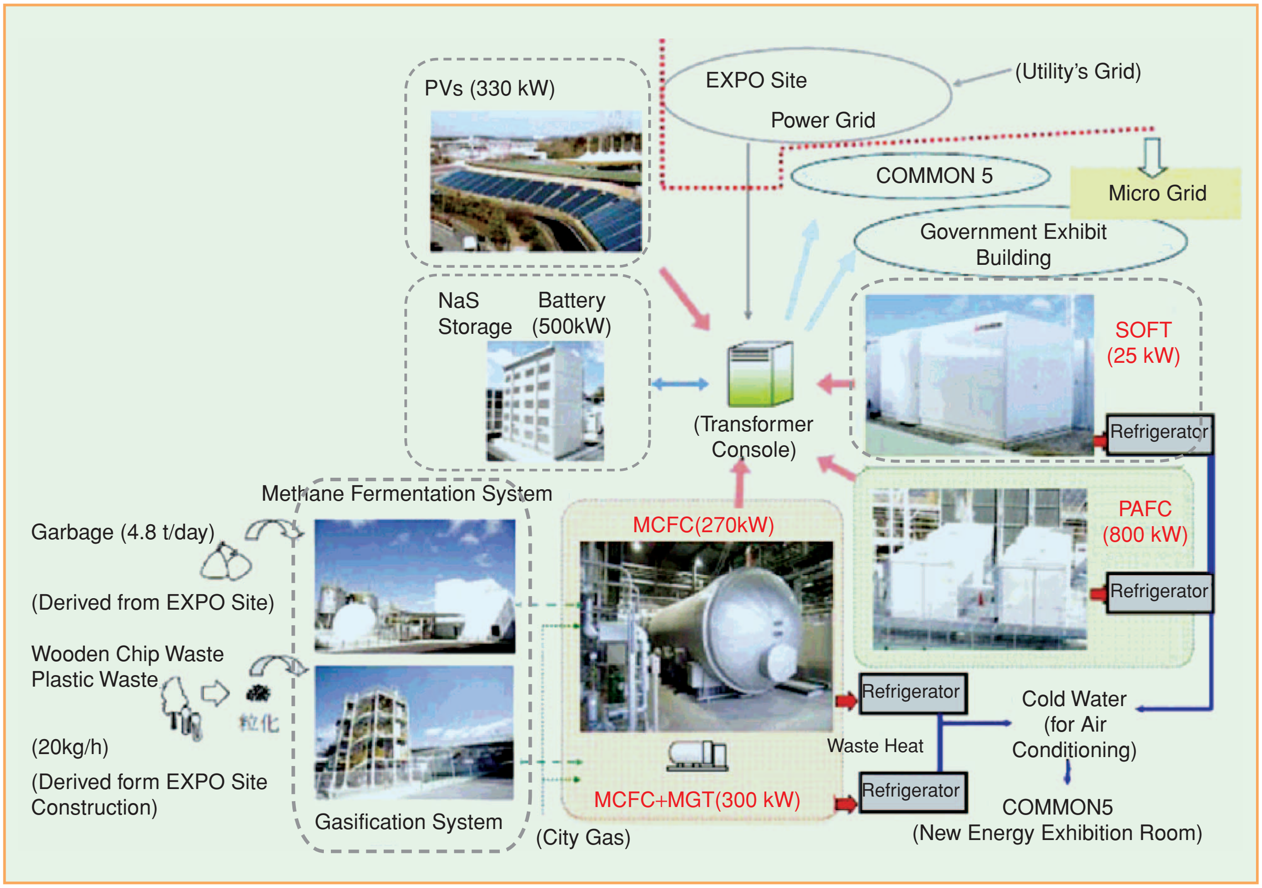


figure 13. Diagram of Aichi Microgrid project.

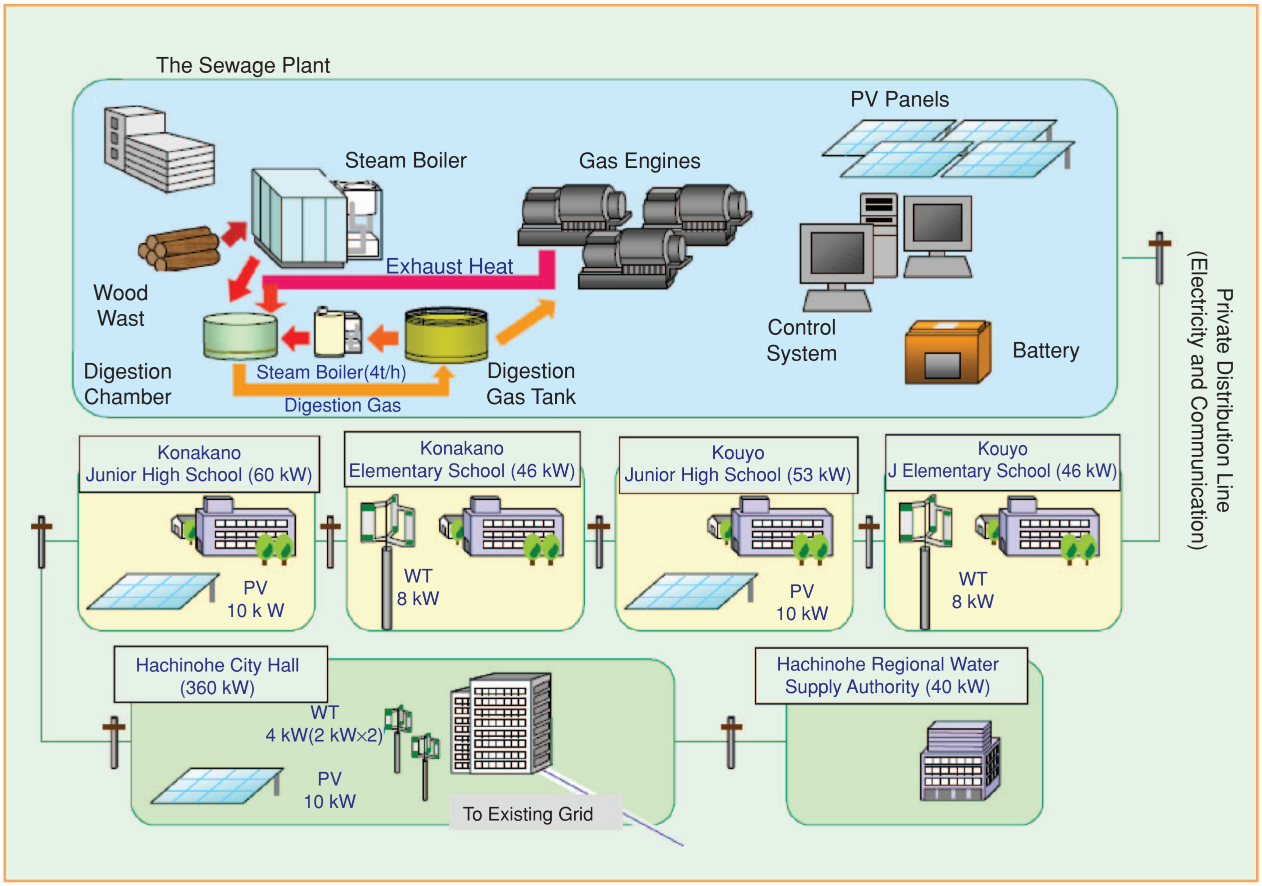


figure 14. Overview of the Hachinohe project.

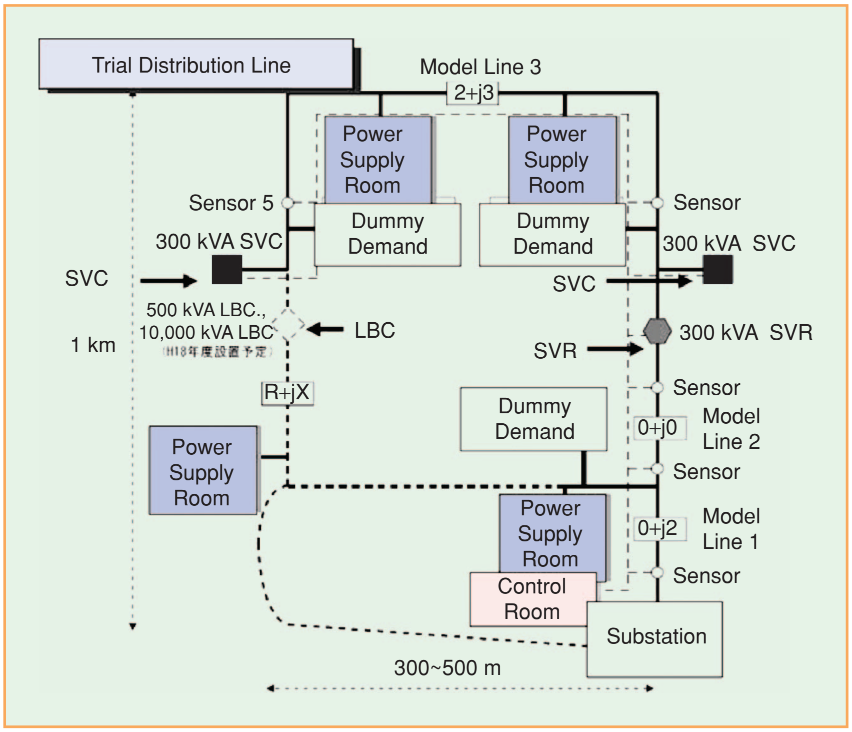


figure 15. Structure of test network at CRIEPI.

can achieve and maintain the same power quality level as a utility network. In the plant, gas engines with a total capacity of 400 kW were installed together with a 250-kW MCFC and a 100-kW lead-acid battery. In remote locations, two PV systems and one 50-kW small wind turbine were also installed. The power generation equipment and end-user demand are managed by remote monitoring and control. One of the interesting features of the system is that it is managed not by a state-of-the-art information network system but by conventional information networks, which are the only network systems available in rural areas.

The Hachinohe project (Figure 14) features a microgrid system constructed using a private distribution line measuring more than 5 km. The private distribution line was constructed to transmit electricity primarily generated

> Distributed storage technologies are used in microgrid applications where the generation and loads of the microgrid cannot be exactly matched.

by the gas engine system. Several PV systems and small wind turbines are also connected to the microgrid. At the sewage plant, three 170-kW gas engines and a 50-kW PV system have been installed. To support the creation of digestion gas by the sewage plant, a wood-waste steam boiler was also installed due to a shortage of thermal heat to safeguard the bacteria. Between the sewage plant and city office, four schools and a water supply authority office are connected to the private distribution line. At the school sites, renewable energy resources are used to create a power supply that fluctuates according to weather conditions in order to prove the microgrid's control system's capabilities to match demand and supply. The control system used to balance supply and demand consists of three facets: weekly supply and demand planning, economic dispatch control once every three minutes, and second-by-second power flow control at interconnection points. The control target is a margin of error between supply and demand of less than 3% for every six-minute interval. During testing, a margin of error rate of less than 3% was achieved during 99.99% of the system's operational time. The Hachinohe project experienced one week of grid-independent operation in November 2007. In this operational mode, imbalance among the three phases was compensated by the PV converter.

The New Power Network Systems project is evaluating new test equipment installed on a test distribution network (Figure 15) constructed at the Akagi Test Center of the Central Research Institute of the Electric Power Industry (CRIEPI). This equipment includes a static var compensator (SVC), a step voltage regulator (SVR), and loop balance controllers (LBCs). The SVC and SVR are used for controlling the voltage on a distribution line, and they are sometimes applied on an actual utility network. In this project, the effects of integrated control of this equipment are being examined. LBCs are a new type of distribution network equipment that can control the power flow between two distribution feeders by means of a back-to-back (BTB) type converter. The LBCs allow connections of two sources with different voltages, frequencies, and phase angles by providing a dc link.

A final microgrid project is evaluating the possibility that grid technology can create value for consumers and various energy service levels. In Sendai City a microgrid consisting of two 350-kW gas engine generators, one 250-kW MCFC, and various types of compensating equipment is being evaluated to demonstrate four levels of customer power. Two of the service levels will have compensating equipment that includes an integrated power quality backup system that supplies high-quality

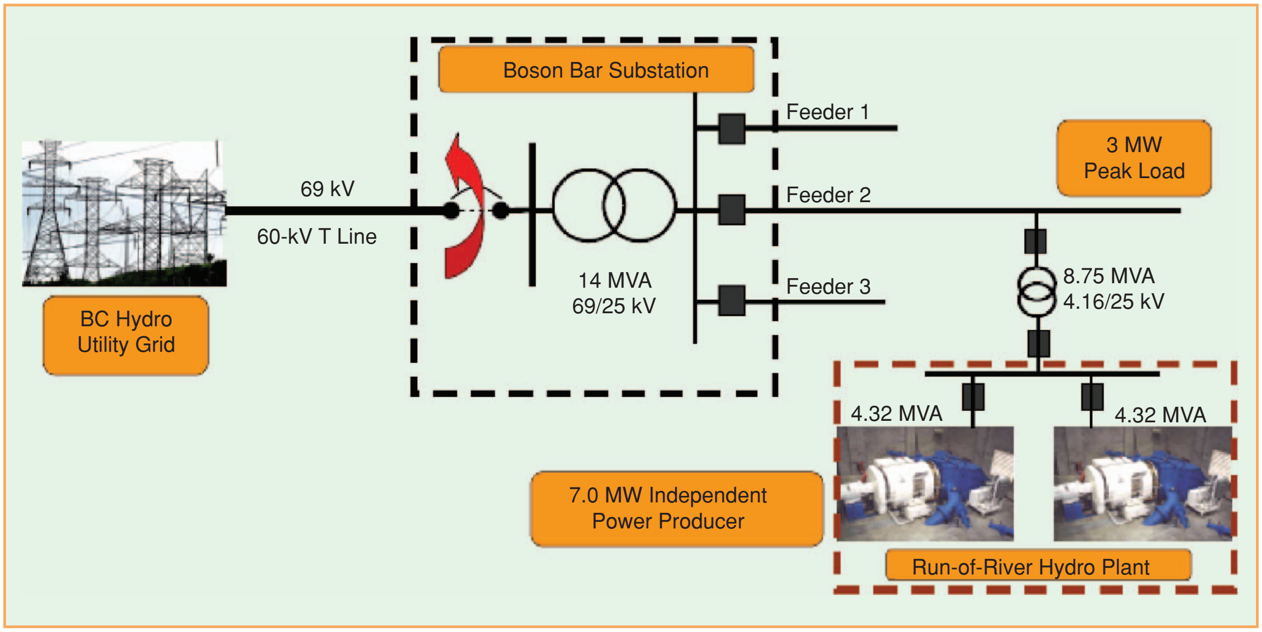
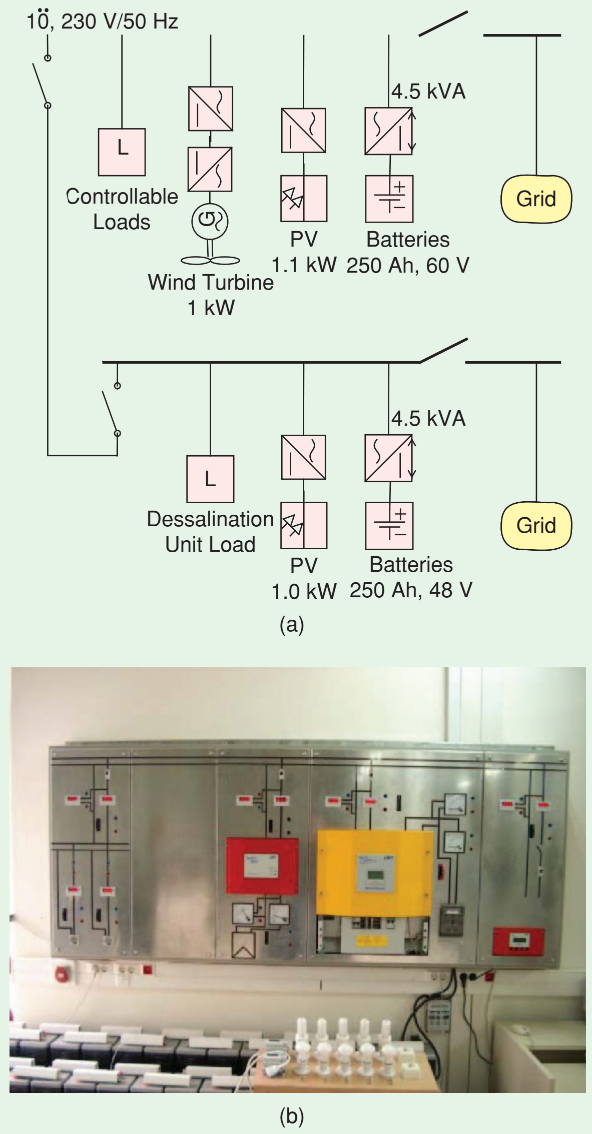


figure 16. System configuration for the Boston Bar IPP and BC Hydro planned islanding site.

power that reduces interruptions and voltage drops. In one of these cases, the wave pattern is guaranteed. Two additional lower service levels have only short-term voltage drops compensated by a series compensator. This work will evaluate the possibility of providing various service levels to customers located in the same area. Since summer of 2007, the Sendai system has been in operation and has improved the power quality at the site. Before starting actual operation, the compensation equipment was tested by using a BTB power supply system to create artificial voltage sag.

In addition to the NEDO-sponsored projects, there are several private microgrid projects. Tokyo Gas has been evaluating a 100-kW microgrid test facility since September 2006 at the Yokohama Research Institute, consisting of gas-engine combined heat and power (CHP), PV, wind power, and battery-incorporated power electronics. Shimizu Corp. has developed a microgrid control system with a small microgrid that consists of gas engines, gas turbines, PV, and batteries. The system is designed for load following and includes load forecasting and integrated control for heat and power.



(a)

(b)

figure 17. Laboratory microgrid facility at NTUA, Greece: (a) single-line diagram and (b) view of one pole.

Testing Experience in Canada

Planned microgrid islanding application, also known as intentional islanding, is an early utility adaptation of the microgrid concept that has been implemented by BC Hydro and Hydro Quebec, two of the major utility companies in Canada. The main objective of planned islanding projects is to enhance customer-based power supply reliability on rural feeders by utilizing an appropriately located independent power producer (IPP), which is, for instance, located on the same or adjacent feeder of a distribution substation. In one case, the customers in Boston Bar town, part of the BC Hydro rural areas, which is supplied by three 25-kV medium-voltage distribution feeders, had been exposed to power outages of 12 to 20 hrs two or three times per year. This area, as shown in Figure 16, is supplied by a 69/25-kV distribution substation and is connected to the BC Hydro high-voltage system through 60 km of 69-kV line. Most of the line is built off a highway in a canyon that is difficult to access with high potential of rock/mud/snow slides. The implemented option to reduce sustained power-outage durations is based on utilizing a local IPP to operate in an intentional island mode and supply the town load on one or more feeders of the substation. The Boston Bar IPP has two 3.45-MW hydro power generators and is connected to one of the three feeders with a peak load of 3.0 MW. Depending on the water level, the Boston Bar IPP can supply the community load on one or more of the feeders during the islanding operation. If the water level is not sufficient, the load on one feeder can be sectioned to adequate portions.

Based on the BC Hydro islanding guideline, to perform planned islanding, an IPP should be equipped with additional equipment and control systems for voltage regulation, frequency stabilization, and fault protection. In addition, the island-load serving capability of an IPP needs to be tested prior to and during the project commissioning to ensure that the IPP can properly respond to load transients such as a step change in load and still sustain the island.

The functional requirements added to the Boston Bar IPP to support planned islanding are as follows:

- ✔ governor speed control with fixed-frequency (isochronous) mode for single-unit operation and speed-droop settings for two-unit operation in parallel
- ✔ engineering mass of generators and hydro turbines to increase inertia and improve transient response
- ✔ excitation system control with positive voltage field forcing for output current boost during the feeder fault to supply high fault current for proper coordination of protection relays

- automatic voltage regulation control to regulate voltages at the point of common coupling
- two sets of overcurrent protection set-points for the grid-connected and the islanding operating modes
- real-time data telemetry via a leased telephone line between the IPP remote control site and the utility area control center
- black start capability via an onsite 55-kW diesel generator.

In addition to the above upgrades, the auto-recloser on the connecting IPP feeder is equipped with a secondary voltage supervision function for voltage supervisory close and blocking of the auto-reclosing action. Remote auto-synchronization capability was also added at the substation level to synchronize and connect the island area to the 69-kV feeder without causing load interruption. When a sustain power outage event, such as a permanent fault or line breakdown, occurs on the utility side of the substation, the main circuit breaker and feeder reclosers are opened (Figure 16). Then, the substation breaker open position is telemetered to the IPP operator. Subsequently, the IPP changes the control and protection settings to the island mode and attempts to hold the island downstream of the feeder 2 recloser. If the IPP fails to sustain the island, the IPP activates a black-start procedure and picks up the dead feeder load under the utility supervision. The island load may be supplied by one generator or both generators in parallel.

Two sets of tests were performed during the generator commissioning as follows:

1) grid parallel operation tests including a) the automatic and manual synchronization, and b) output load, voltage and frequency controls, and load rejection tests
2) island operation tests comprising a) load pick-up and drop-off tests in 350-kW increments, b) dead load pick-up of 1.2 MW when only one of the two generators is in operation, and c) islanded operation and load following capability when one unit is generating and/or both units are operating in parallel.

The planned islanding operation of the Boston Bar IPP has been successfully demonstrated and performed several times during power outages caused by adverse environmental effects. Building on the knowledge and experience gained from this project, BC Hydro has recently completed a second case of planned islanding and is presently assessing a third project.

Testing in Europe

At the international level, the European Union has supported two major research efforts devoted exclusively to microgrids: the Microgrids and More Microgrids projects. The Microgrids project focused on the operation of a single microgrid, has successfully investigated appropriate control techniques, and demonstrated the feasibility of microgrid operation through laboratory experiments. The Microgrids project investigated a microgrid central controller (MCC) that promotes technical and economical operation, interfaces with loads and micro sources and demand-side management, and provides set points or supervises local control to interruptible loads and micro sources. A pilot installation was installed in Kythnos Island, Greece, that evaluated a variety of DER to create a microgrid.

Continuing microgrid projects in Greece include a laboratory facility (Figure 17) that has been set up at the National

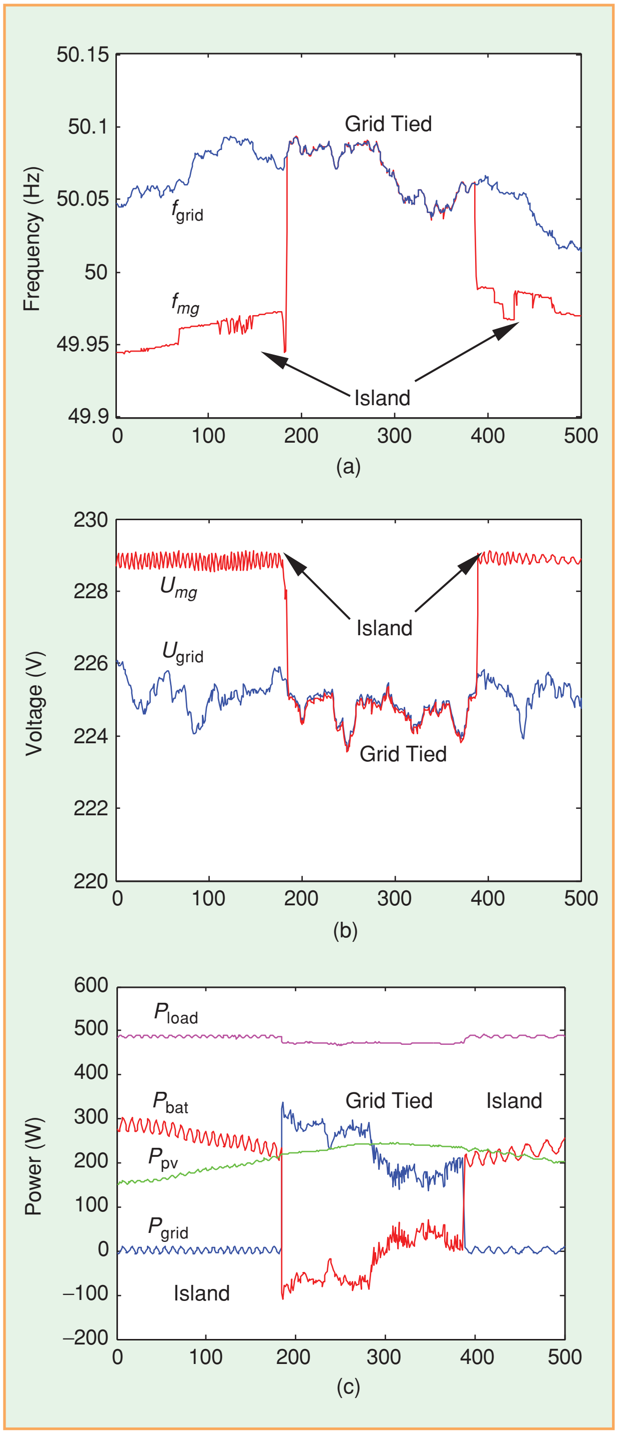


figure 18. Changes of the microgrid operating mode from island to interconnected mode and vice-versa: (a) frequency, (b) voltage, and (c) component powers.

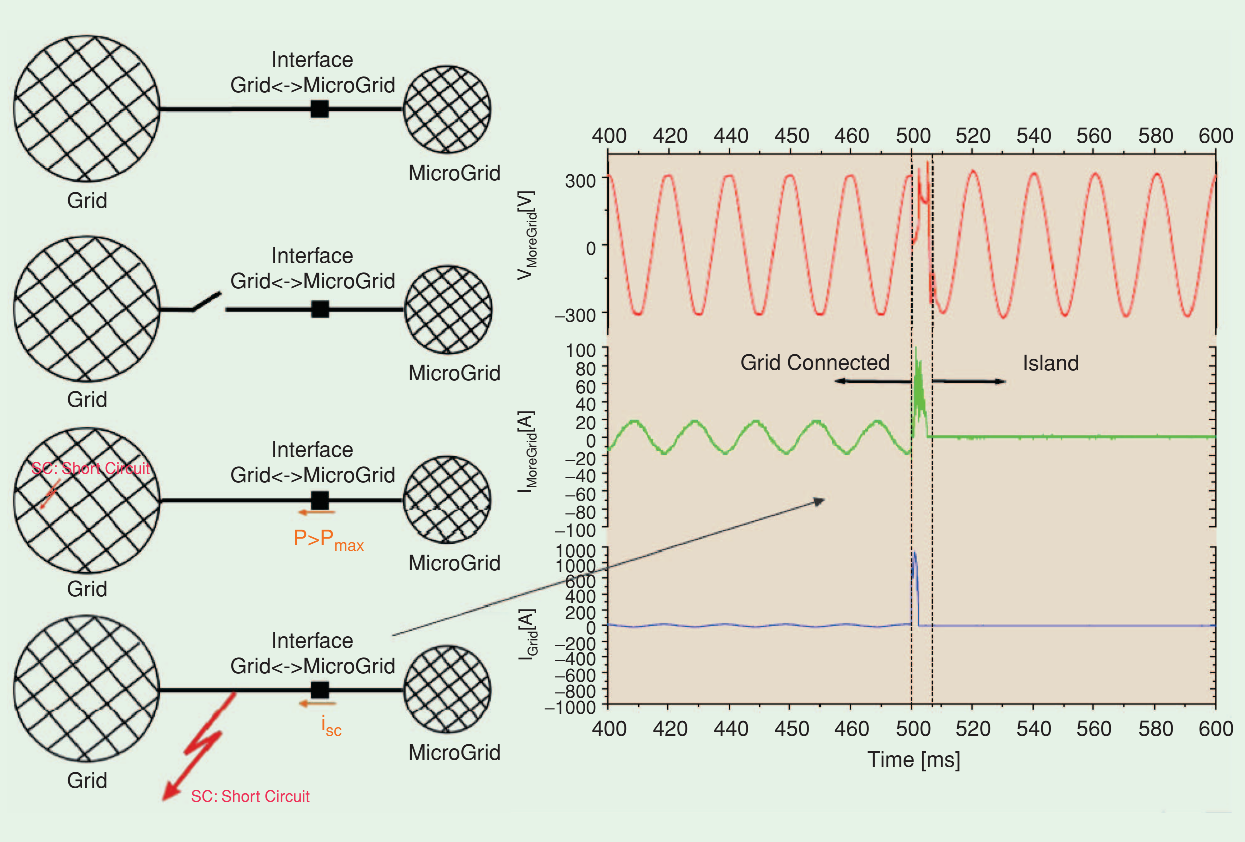


figure 19. Voltage and current changes as the microgrid switches to islanded mode.

Technical University of Athens (NTUA), with the objective to test small-scale equipment and control strategies for microgrid operation. The system comprises two poles, each equipped with local (PV and wind) generation and battery storage, connected to each other via a low-voltage line as well as to the main grid. Each pole may operate as a microgrid via its own connection to the grid, or both poles may be connected via the low-voltage line to form a two-bus microgrid connected to the main grid at one end. The battery converters are the main regulating units in island mode, regulated via active power-frequency and reactive power-voltage droops. Multi-agent technology has been implemented for the control of the sources and the loads.

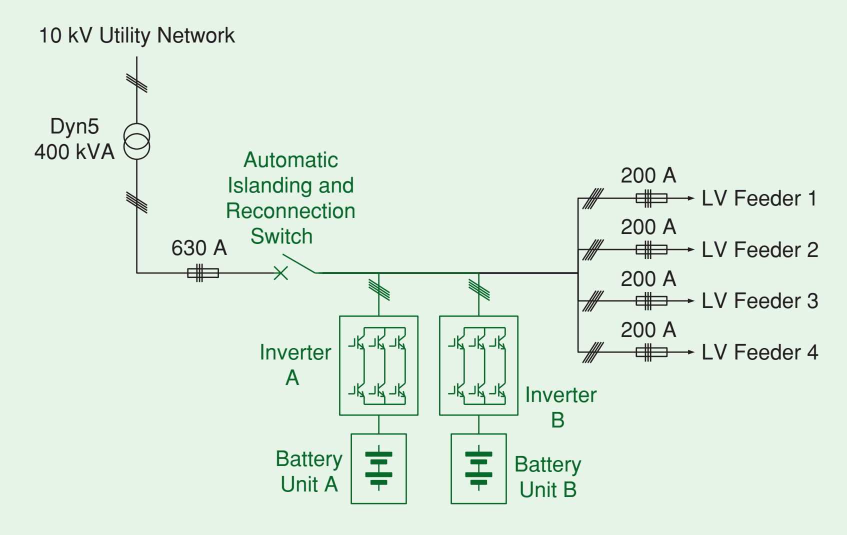


figure 20. Schematic for the Bronsbergen Holiday Park microgrid.

Figure 18 shows indicative test results demonstrating the seamless transition of the microgrid from grid-connected to island mode and vice-versa (one-pole microgrid operation). The first diagram illustrates the variation of the frequency and the second of the voltage. The change of the component power flows is shown in the third illustration. While the load and the PV continue operating at the same power, the output of the battery converter and the power flow from the grid change to maintain the power equilibrium in the microgrid.

Testing on microgrid components has also been extensively conducted by ISET in Germany. Figure 19 shows testing conducted to examine voltage and current transient when microgrids transfer from grid-connected to islanded mode. This figure shows that with proper design, there can be minimal load disruption during the transfer.

The More Microgrids project aims at the increase of penetration of microgeneration in electrical networks through the exploitation and extension of the Microgrids concept, involving the investigation of alternative microgenerator control strategies and alternative network designs, development of new tools for multimicrogrid management operation and standardization of technical and commercial protocols, and field trials on actual microgrids and evaluation of the system performance on power system operation.

One of the More Microgrids projects is located at Bronsbergen Holiday Park, located near Zutphen in the Netherlands. It comprises 210 cottages, 108 of which are equipped with grid-connected PV systems. The park is electrified by a traditional three-phase 400-V network, which is connected to a 10-kV medium-voltage network via a distribution transformer located on the premises (Figure 20). The distribution transformer does not feed any low-voltage loads outside of the holiday park. Internally in the park, the 400-V supply from the distribution transformer is distributed over four cables, each protected by 200-A fuses on the three phases. The peak load is approximately 90 kW. The installed power of all the PV systems together is 315 kW. The objective of this project is experimental validation of islanded microgrids by means of smart storage (coupled by a flexible ac distribution system) including evaluation of islanded operation, automatic isolation and reconnection, fault level of the microgrid, harmonic voltage distortion, energy management and lifetime optimization of the storage system, and parallel operation of converters.

Another More Microgrids project involves field test on the transfer between interconnected and islanding mode with German utility MVV Energie. MVV Energie is planning to develop an efficient solution to cope with the expected future high penetration of renewable energy sources and distributed generation in the low-voltage distribution grid. If integrated in an intelligent way, these new players in the distribution grid will improve independence from energy imports, reliability, and power quality at lower cost than the "business as usual" regarding replacement or reinforcement of the regional energy infrastructure. A successful transfer between interconnected and islanding mode would provide a substantial benefit for the grid operator.

This project will evaluate decentralized control in a residential site in the ecological settlement in Mannheim-Wallstadt. The new control structures for the decentralized control with agents will be tested and allow the transition from grid connection to islanding operation without interruptions. This would improve reliability of the grid and support for black start after failure of the grid.

The CESI RICERCA test facility in Italy will also be used to experiment, demonstrate, and validate the operation of an actual microgrid field test of different microgrid topologies at steady and transient state and power quality analysis. During a transient state, the behavior during short-duration voltage variation for single/three-phase ac faults, or dynamic response to sudden load changes and to conditions of phase imbalance or loss of phase, the islanding conditions following interruption of the supply will be analyzed.

Conclusions

Microgrids will provide improved electric service reliability and better power quality to end customers and can also benefit local utilities by providing dispatchable load for use during peak power conditions and alleviating or postponing distribution system upgrades. There are a number of active microgrid projects around the world involved with testing and evaluation of these advanced operating concepts for electrical distribution systems.

For Further Reading

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