INVITED PAPER

Smart Distribution: Coupled Microgrids

The author of this paper believes that use of microgrids can simplify implementation of many Smart Grid functions, including reliability, self-healing, and load control.

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ABSTRACT | The distribution system provides major opportunities for smart grid concepts. One way to approach distribution system problems is to rethinking our distribution system to include the integration of high levels of distributed energy resources, using microgrid concepts. Basic objectives are improved reliability, promote high penetration of renewable sources, dynamic islanding, and improved generation efficiencies through the use of waste heat. Managing significant levels of distributed energy resources (DERs) with a wide and dynamic set of resources and control points can become overwhelming. The best way to manage such a system is to break the distribution system down into small clusters or microgrids, with distributed optimizing controls coordinating multimicrogrids. The Consortium for Electric Reliability Technology Solutions (CERTSs) concept views clustered generation and associated loads as a grid resource or a "microgrid." The clustered sources and loads can operate in parallel to the grid or as an island. This grid resource can disconnect from the utility during events (i.e., faults, voltage collapses), but may also intentionally disconnect when the quality of power from the grid falls below certain standards. This paper focuses on DER-based distribution, the basics of microgrids, possibility of smart distribution systems using coupled microgrid and the current state of autonomous microgrid technology.

KEYWORDS | Consortium for Electric Reliability Technology Solutions (CERTS); cooling heat and power (CHP); clustered microgrids; distributed generation; intentional islanding; microgrid; smart distribution; uninterruptible power supply (UPS)

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I. INTRODUCTION

Economic, technology and environmental incentives are changing the face of electricity generation and transmission. Centralized generating facilities are giving way to smaller, more distributed energy resources partially due to the loss of traditional economies of scale. Distributed Energy Resources (DER) encompasses a wide range of prime mover technologies, such as internal combustion (IC) engines, gas turbines, microturbines, photovoltaic systems, fuel cells, wind-power and ac storage. Most emerging technologies such as microturbines, photovoltaic systems, fuel cells and ac storage have an inverter to interface with the electrical distribution system. These emerging technologies have lower emissions and the potential to have lower cost negating traditional economies of scale. The applications include power support at substations, deferral of T&D upgrades, high fuel efficiency through capturing waste heat, use of renewable energy, higher power quality and smarter distribution systems.

Today's high voltage transmission network is reliable and controllable but suffers from cascading failures. Its efficiency and use of resources are also poor. Central plants are at best 35% efficient because of line losses and smoke stack waste heat. Approximately 20% of the generation capacity exists to meet peak demand 5% of the time. These issues become compounded with high penetration of renewable sources due to their intermittent behavior.

Revolutionary changes are not expected in the transmission network but improvement through continued evolution can greatly reduce events like the 2003 blackout [1]. The distribution system provides major opportunities for smart grid concepts. Public policies involving global climate change initiatives, reductions in CO_2 and other polluting emissions, and incentives for renewable energy will increase issues related to the distribution system. The retail customers also have increasingly sophisticated energy service requirements that require much higher power quality than in the past. The distribution system needs to be redesigned assuming high levels of distributed energy

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resources, creating a smarter and more flexible system. Basic objectives of a DER-based distribution system are improved reliability, high penetration of renewable sources, dynamic islanding, distributed control and increase generation efficiencies through the use of waste heat.

For distribution systems to utilize the emerging diversity of DER technology at significant levels of penetration the basic distribution pyridine needs to be rethought. Managing such a wide and dynamic set of resources and control points can become overwhelming. The best way to manage such a system is to break the distribution system down into small clusters or microgrids, with distributed optimizing controls coordinating multi-microgrids.

Microgrids are integrated energy systems consisting of interconnected loads and distributed energy resources which as a system can operate in parallel with the grid or in an intentional island mode. Dynamic islanding is a key feature of a microgrid. Numerous benefits accrue from this ability to island for events like faults and voltage sags. Smart islanding can greatly enhances the value proposition for the utility and the customer [2].

This paper focuses on DER-based distribution, the basics of microgrids, possibility of smart distribution systems using coupled microgrid and the current state of microgrid technology.

II. DER-BASED DISTRIBUTION

Using DER in the distribution system reduces the physical and electrical distance between generation and loads. Bring sources closer to loads contributes to enhancement of the voltage profile, reduction of distribution and transmission bottlenecks, lower losses, enhances the use of waste heat, and postpones investments in new transmission and large scale generation systems [3].

Taking Portugal as an example; the losses at the transmission level are about 1.8 to 2%, while losses at the distribution grids are about 4%. This amounts to total losses of about 6% excluding the low voltage network. In 1999 Portugal's power consumption was about 18 TWh. This means that large integration of DER, say 20% of the load, can result in a reduction of losses of at least, 216 GWh. Distributed generation can therefore reduce losses in the European transmission and distribution networks by 2–4%, contributing to a reduction of 20 million tons CO_2 per year in Europe.

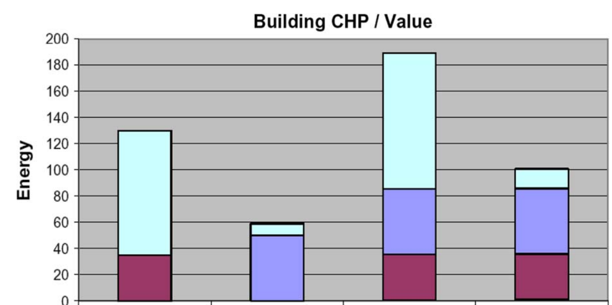
A basic issue for DER is the technical difficulties related to control of a significant number of distributed energy sources. For example California distributed generation objectives could translate to 120 000 one hundred kilowatt generators on their system. If you include renewable goals the number of DER units are much greater. This issue is complex but the call for extensive development in fast sensors and complex control has a potential for disaster. The fundamental problem with a complex control system is that a failure of a control component or a software error could bring the system down. DER units in the distribution system need to be able to respond to events autonomously using only local information, i.e., voltage, current and frequency. For voltage drops, faults, blackouts etc. the DER with local loads needs to switch to island operation. This will require an immediate change in the output power control of the generators as they change from a dispatched power mode to one controlling frequency of the islanded section of the network along with meeting the demands of the islanded loads.

The two major benefits of DER-based distribution are increased efficiencies using waste heat and reduction of line losses and enhanced customer reliability through islanding during a power system outage. The major roadblock is system complexities of managing such a wide and dynamic set of resources and control points.

A. Optimal Location for Use of Waste Heat

The use of waste heat through cogeneration or combined cooling heat and power (CCHP) implies an integrated energy system, which delivers both electricity and useful heat from an energy source such as natural gas. Most existing power plants, central or distributed, deliver electricity to user sites at an overall fuel-to-electricity efficiency in the range from 28 to 32%. This represents a loss of around 70% of the primary energy provided to the generator. Fig. 1 indicates that a system, which independently generates electricity and heat from natural gas, has a combined efficiency of 45%. This is compared with a CHP system for the same electrical and heat loads. This CHP system efficiency is 85% [4]. To reduce energy losses it is necessary to either increase the fuel-to-electricity efficiency of the generation plant and/or use the waste heat.

The size of emerging distributed generation technologies permits generators to be placed optimally in relation to heat loads. The scale of heat production from individual



	Electricity	Heat	Combined	CHP
Losses	95	9	104	15
Heat		50	50	50
Electricity	35		35	35
Efficiency			45%	85%

Fig. 1. ***Combined heat and power.***

units is small and therefore offers greater flexibility in matching heat requirements. For example, fuel cells could be placed on every floor of a hospital to match each floor's hot water needs and provide electricity to the hospital's electrical loads.

B. Power Quality and Reliability

Many industrial, commercial and residential customers now require a high level of power quality due to the increase of digital systems and sophisticated controls. These customers are especially sensitive to momentary voltages sags caused by remote faults. Power quality, availability and reliability are important issues to all customers. There have been proposals to create a more reliable power system using two-way command and control systems with "smart" meters to meet customers' demands. This approach is complex and costly and is not necessary if DER is well integrated with the distribution system. DER has the potential to increase system reliability and power quality due to the decentralization of supply. Clusters of DER units and loads can be designed to island during a system disturbance providing the necessary levels of power quality, availably and reliability required by the customer.

It has been found that, in terms of energy source security, that multiple small generators are more efficient than relying on a single large one for lowering electric bills [5]. Small generators are better at automatic load following and help avoid large standby charges seen by sites using a single generator. Having multiple DER units in a microgrid makes the chance of all-out failure much less likely, particularly if extra generation is available.

DER based distribution can be better organized using many connected building blocks or microgrids. Each microgrid consists of clustered DER units and loads creating a component with known characteristics. For example large generation can provide real and reactive power to the power system over a known operating range while loads consume a known real and reactive power. This enables the operation and control of the power system. The microgrid is a new grid resource that provides or absorbs a know range of real and reactive power depending on the details of its internal components. Unlike generation or loads a microgrid can seamlessly move between being a grid resource and a standalone island providing energy for local loads.

III. MICROGRID

Application of individual distributed energy resources, DER, can cause as many problems as it may solve. A better way to realize the emerging potential of distributed energy resources is to take a system approach viewing DER and associated loads as a grid resource or a "microgrid" [6]. The sources and loads can operate in parallel to the grid or as an island. It can provide for the customer's critical needs while providing services to the distribution system. Microgrids can provide the following:

- local load grow and enhance the robustness of the distribution system;
- facilitate greater use of renewable such as small wind and photovoltaic systems;
- increase energy efficiency and the level of local reliability demanded by customers' loads.

Microgrid control is designed to facilitate an intelligent network of autonomous units. Microgrids have an interface switch, DER units and loads. The interface 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. Each DER component can seamlessly control power and provide required energy to each load. The DER units in the islanded microgrid use a power vs. frequency droop controller to track the energy requirements of the loads. If there is inadequate generation the frequency will drop below the normal operating range activating frequency load shedding. The coordination between sources and loads in an islanded microgrid is through frequency [7].

A voltage controller at each DER unit provides local stability. Without local voltage control, systems with high penetrations of DER 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 vs. reactive power droop controller. These concepts are similar to solid-state synchronous voltage sources used on the high voltage power system [8]. 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.

Fig. 2 represents a "grid resource" or microgrid consisting of a variety of loads, distributed energy resources and an interface switch to the distribution system. For example the mixture of loads include both critical and noncritical. The noncritical can be dropped as needed. DER

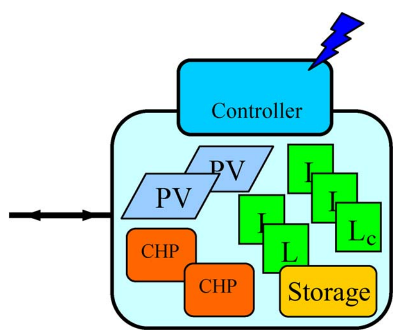


Fig. 2. ***Grid resource or microgrid.***

components encompasses a wide range of power technologies, such as IC engines, synchronous generators, gas turbines, microturbines, photovoltaic panels, fuel cells, wind-turbines and storage systems. Each DER resource has a different response time. For example storage and some fast IC engines can respond in cycles while most micro-turbines require seconds to responding to the same load change [9]. These response times are critical to insure successful islanding. It is important to have fast DER units to insure the energy requirements of the loads can be supplied during the first few cycles after islanding. Fast sources also provide a buffer allowing the slower responding sources to come up to their operating point.

The controller shown in Fig. 2 provides overall system control. This controller interfaces with each DER unit in the microgrid. The objective is to provide a distributed control system to coordinating the operation of multi-microgrids in the distribution system. This communication system is not used for the dynamic operation of the microgrid. The fast dynamic needs are provided through autonomous control at each DER units. This controller not only optimizes the internal operation of the microgrid, it can also respond to system request for real and reactive power flow between the microgrid and the distribution system. Different microgrid objectives can be achieved depending on the mix of DER units and loads. Three major possibilities are high power quality microgrids with effective use of waste heat, multi-MW microgrids and microgrids designed to export high levels of PV energy.

A. High Power Quality Microgrid With CCHP

Microgrid components must follow peer-to-peer and plug-and-play concepts to insure high power quality and effective use of waste heat. Each source is connected in a peer-to-peer fashion with a localized control scheme implemented for each component. This arrangement increases the reliability of the system in comparison to having a master-slave or centralized control scheme. In the case of master–slave controller architecture the failure of the master controller could compromise the operation of the whole system. Plug and play concepts allow us to expand the microgrid to meet the requirements of the site without extensive reengineering. This implies that the microgrid can continue operating with loss of any component or generator. With one additional source, $(N+1)$, we can insure complete functionality with the loss of any source. The plug-and-play model facilitates placing generators near the heat loads thereby allowing more effective use of waste heat without complex heat distribution systems such as steam and chilled water pipes.

Dispatchable microsources, such as small variable speed internal combustion IC engine driving a synchronous generator or a microturbine require an inverter interface. Sources need a fast-response energy storage module to minimize the impacts of source dynamics on the microgrid operation, [10]. The storage can be batteries or supercapacitors that are connected to the dc bus of each source. DC storage has several advantages over ac storage. First, the dc storage decouples dynamics of a source from those of the microgrid. Second, the dc storage promotes peer-to-peer concepts, where each source has the energy storage required for a fast dynamic response and is not dependent to a central ac storage system. This modularly promotes high reliability since loss of one storage module does not significantly impact the operation of microgrid. In contrast, the loss of a central AC storage system can greatly reduce the functionality of the microgrid. High power quality microgrids have been successfully studied at the AEP/CERTS Microgrid Test facilities [11].

B. Multi-MW Based Microgrid

Scaling microgrid technology to higher voltages and power levels change the DER mix. High power quality applications based on peer-to-peer models and inverter-based interfaces are less practical. Cost of inverters become prohibitive compared to other alternatives at the several megawatt level. It is preferred to operate a synchronous generator directly connected to the microgrid [12]. In this case the governor and exciter need to be modified to comply with CERTS Microgrid criteria. The shortcoming is response time. Generally synchronous generator's response is too slow to support seamless islanding. A microgrid using direct connected synchronous generation will also need an inverter-based energy sources to support islanding. There are three possibilities energy sources requiring an inverter interface. They are fuel cells, ac storage and photovoltaic arrays. Fuel cells are basically fixed sourced systems requiring large dc storage to support islanding. Photovoltaic arrays have the fast response provided there is solar energy, but in general ac storage is necessary for microgrids using direct connected synchronous generators.

The simplest distribution microgrid consist of several directly connected synchronous generators and ac storage. AC storage provides the fast power changes required for islanding and load tracking. The generators provide the base load power. In this model the DER units still follow the plug-and-play and autonomous control model but loss of ac storage can inhibit seamless islanding.

C. PV Microgrid

Currently the relatively low penetration levels of renewable systems cause few problems. As penetration becomes greater the availability of sun becomes a greater problem requiring central generation to provide the power backup. Such systems are intermittent and can cause similar stability problems found with intermittent loads such as rolling mills and arc furnaces. Central generation or DER units are required to smooth out power fluctuations from these renewable sources. In any case there is a need for reserves when there is no sun. An obvious solution includes DER units on the distribution system. Without storage and/or local generation there is a technical limit to the amount of PV generation on the distribution system. Systems with high levels of PV penetration need to be supplemented with local "dispatchable" resources such as storage and local generation to fill-in for temporary loss of solar energy.

PV microgrids can be designed for high export of PV energy without the short-term problems associated with intermittent power fluctuations. The DER units in a PV microgrid can have multi-roles such as control of real and reactive power flow between the microgrid and distribution system, power fill-in when intermittent generation is not available and local load support during islanding. Typically a PV micorgrid has photovoltaic energy for export, local generation and/or storage. The generation and storage provide the fill-in energy required to smooth out or shape the power provided to the distribution system. The inverter based AC storage allows the generation to be connected directly to the microgrid without an inverter. If storage is not used the generation need the fast response provided through an inverter interface.

Islanding a PV microgrid has special issues. For example a PV microgrid may have PV power levels greater than the loading when islanded. This requires either high storage capacity to absorb the extra energy or have methods of reducing the power output of the solar panel. The power vs. frequency droop controller provides an elegant method of backing off the solar output during low load islanding. An island with excess generation will experience an increase in frequency which autonomously reduces the output of generation, moves storage to a charging mode and smoothly backs off the PV output as necessary.

IV. SMART DISTIBUTION

Smarter distribution can be achieved through the fast control of hundreds of individual DER units. This would require real time information on each DER unit and key loads. The control complexity and reliability of such a system is greatly reduced using coupled microgrids. First a systems consisting of many microgrids does not need fast communication as discussed above and demonstrated at the AEP test site. Second any communication system would re-dispatch each microgrid without needing detailed information on each DER unit.

Recall that the basic smart distribution system objectives include improved reliability, self-healing, simplified controls and increased generation efficiencies through the use of waste heat. Improved reliability, simplified controls and increased efficiencies are imbedded in the basic microgrid concepts. A microgrid can operate in parallel to the grid or as an island. It can disconnect from the utility during events (i.e., faults, voltage collapses), but may also intentionally disconnect when the quality of power from the grid falls below certain standards providing higher power quality and availably to these loads within the island. Clustering of load and sources insure efficiencies due to reduced losses and the potential to use waste heat. The control complexity problems are reduced from controlling all the DER units to dispatching microgrids. A microgrid's number and type of DER units is no longer relevant for the dispatch of its resources. For example in the traditional model a control center dispatches each generator's real and reactive power output to meet the expected demands of loads and in some situations can curtail loads, (i.e., smart loads). The microgrid is a different grid resource that provides or absorbs over a know range of real and reactive power depending on the details of the microgrid. A microgrid can respond to request for load reduction by increasing its internal generation and/or by turning off some none critical loads. Critical to implementing smart distribution concepts is information from each microgrid on the range of real and reactive power available for dispatch. A PV microgrid could receive a request for all available renewable power.

To illustrate possible self-healing envision a multi-MW microgrid connected to a 12 kV substation using a fast interface switch. Connected to this microgrid are several lower voltage high-power quality microgrids with fast interface switches. This example assumes the only controls are the autonomous algorithms at each DER unit and the interface switchs. The simplest MW microgrid could consist of several synchronous generators and storage. The low-voltage, high-power quality microgrids would typically have fast inverter-based sources. Each source is connected in a peer-to-peer and plug-and-play fashion with autonomous controls.

A voltage collapse at the distribution substation would island the multi-MW microgrid with the opening of the interface switch. The storage unit would supply the lost energy within a few milliseconds with the synchronous generators increasing their output at a slower rate. In the end the storage would autonomously modify it's output in cooperation with the generators. The islanded system would settle at a lower frequency based on the power vs. frequency droop characteristics. The two other interface switches would open either on the original event or this frequency droop. This fast islanding along with fast changes in power output provides uninterruptible power supply (UPS) quality of power to the low voltage loads. If the multi-MW microgrid did not have sufficient generation to support all of its loads the frequency would continue to drop trigging load shedding of low priority loads. The new steady state consisted of three islanded microgrids supporting their respective loads. When the substation voltage returns to normal the multi-MW microgrid interface switch would seamless reconnect to the utility returning its frequency to that of the utility. This frequency change would allow the two other microgrids to autonomously reconnect to the distribution microgrid. In summary, this example illustrates self-healing and improved reliability features through the use of coupled microgrids.

V. STATUS OF AUTONOMOUS MICROGRIDS

Autonomous control concepts applied to DER units can greatly simplify the complexity of coupled microgrids in the distribution system. Current test sites have demonstrated the feasibility of using microgrids as a grid resource. This implies configuring each DER component with the same autonomous control characteristics promoting plug-and-play application. These concepts have been implemented in hardware at two test sites. In addition, two field sites are now under construction.

The CERTS/AEP Microgrid Test Bed in Ohio has been actively testing CERTS concepts over the last five years. Testing includes islanding and reconnecting for multiple configurations, power quality performance and protection strategies. Some of the key results are discussed in more detail in the Section VI. The University of Wisconsin has a microgrid test facility. This is a low voltage system with a mix of different DER units with ratings of 15 kW or less. This system has successfully demonstrated an inverter-based microgrid including a smart switch. In the last two years inclusion of battery storage and direct connected synchronous generation as part of the UW microgrid has also been successfully demonstrated [13].

A multi-MW microgrid is being constructed in Alameda County, CA. This system will integrate ac storage, diesel generators, photovoltaic arrays, fuel cells, and wind turbines. The basic feeder is at 12 kV with peak loads close to 3 MWs. Chevron Energy Solutions is the prime contractor. Sacramento Municipal Utility District, (SMUD) is installing a high-power quality microgrid with CHP at its corporate headquarters. SMUD expects to collect power quality and CHP data for several years. The base load is 310 kW with a peak of 375 kW. This system will use three Tecogen Premium Power Modules rated at 100-kilowatt, with CHP and a thyristor-based interface switch.

VI. CERTS/AEP MICROGRID TEST-BED

The CERTS/AEP Microgrid Test Bed is shown in Fig. 3. There are three feeders, with loads and three 60 kW inverter based sources. Two sources are on one feeder, with the third on a parallel feeder. There is also a feeder outside of the static switch. The feeder with two sources has 100 yards of cable between the sources, providing impedance to verify the plug and play and local stability features. These two feeders can be islanded from the utility using a static switch. The static switch hardware consists of back-to-back thyristors with local implement of the CERTS microgrid islanding and resynchronization procedures.

There are four load banks that can be remotely controlled from 0–90 kW and 0–45 kVAR. Each load bank also has remote fault loads which range from bolted faults to high impedance faults (60 and 83 kW). Other loads include a 20 HP induction motor. Additional equipment includes; protection relays, shunt trip breakers and an extensive digital acquisition system. The digital acquisition system includes twelve 7650 ION meters providing detailed voltage and current waveforms for each phase conductor including the neutral.

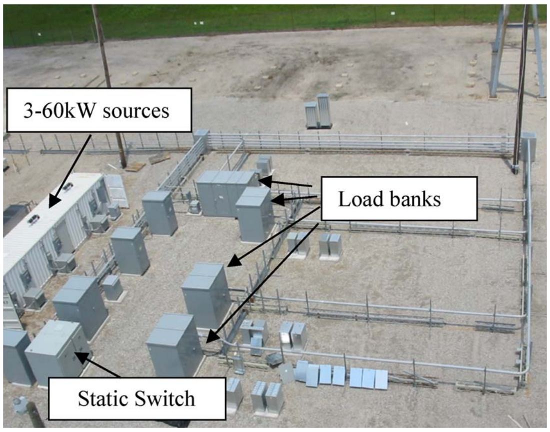


Fig. 3. *CERTS microgrid test-bed (AEP's walnut site).*

When the microgrid is connected to the utility, its loads receive power both from the grid and local DER units. If the grid power is lost because of IEEE 1547 events, voltage sags, faults, blackouts, etc., the microgrid will autonomously transfer to island operation. Fig. 4 shows power versus frequency droop for two of the three sources. For AEP the slope is chosen by allowing the frequency to droop by 0.5 Hz as the power spans from zero to maximum output. Fig. 4 also shows the power set points P_{o1} and P_{o2} for two units. This represents the power dispatched by each unit when connected to the grid. If the system transfers to island when importing from the grid, the generation needs to increase power output to replace the lost power from the utility. The new operating point will be at a frequency lower than the nominal value. In this case both sources have increased their power output with unit 2 reaching its maximum power point. If the system transfers to island when exporting power to the grid, then the new frequency will be higher, corresponding to a lower power output from the sources.

These concepts are demonstrated in three key tests shown in Figs. 5–7. The first case looks at the two sources on the same feeder during islanding [14]. It this case the effectiveness of load sharing and the operation of the power maximum limit are demonstrated. The seconds test shows the smooth response three sources during islanding. The last test demonstrates the high level of power quality achieved using autonomous microgrid concepts.

The characteristics shown in Fig. 4 are steady-state characteristics. They have a fixed slope in the region where the unit is operating within its power range. The slope becomes vertical as soon as any limit is reached. The droop is the locus of steady-state operation point, but during dynamics the trajectory will deviate from these characteristics.

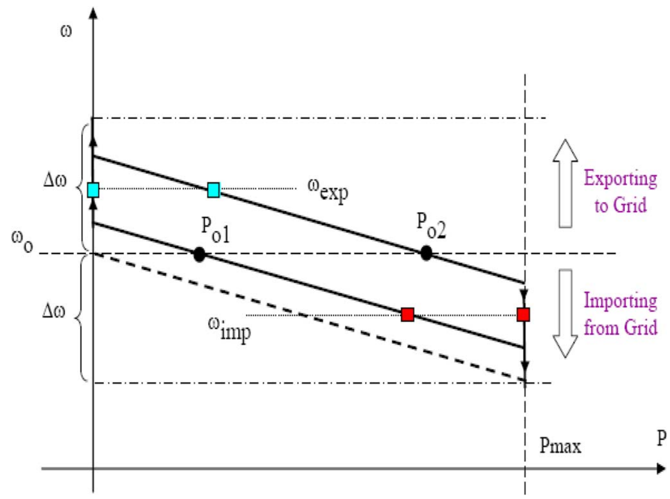


Fig. 4. *Steady-state power versus frequency droop.*

The dynamics of frequency droop is shown in Fig. 5. The figure shows the response of two sources during an islanding event. In this system there is no communication between the two units. Before islanding both sources are connected to the AEP system. The real power output of A-1 is 5 kW and reactive power (capacitive) is close to 9 kVAR, Fig. 5(a). Three phase currents from the source are shown in the middle plot and the lower plot displays voltage at the point of connection to the feeder. Fig. 5(b) traces are measured at unit A-2. Before islanding the power output of A-2 is 55 kW and the reactive power (capacitive) is close to 5 kVAR.

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

Fig. 6 demonstrates microgrid islanding with three sources operating in unit control mode. There are three loads drawing 37 kW and 20 kVAR each. The grid provides 22 kW with the sources providing the remaining 89 kW required by the loads. The top plot in Fig. 6 shows the power imported through the static switch and the power provided by each source. This islanding event

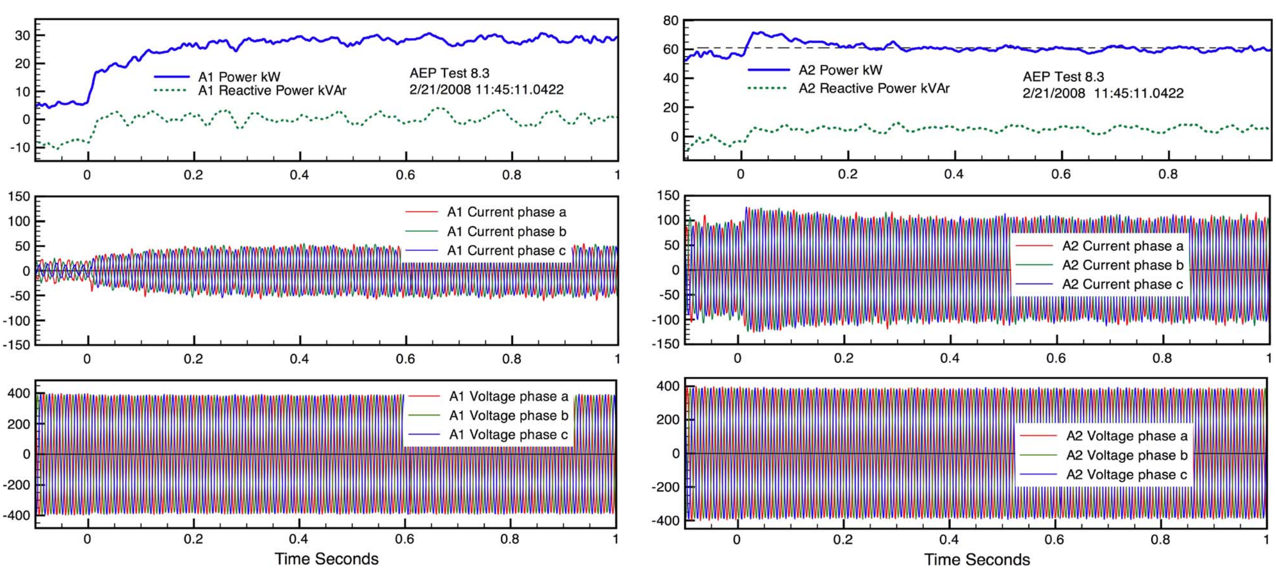


Fig. 5. *(a) Dynamic response of unit A-1. (b) Dynamic response of unit A-2.*

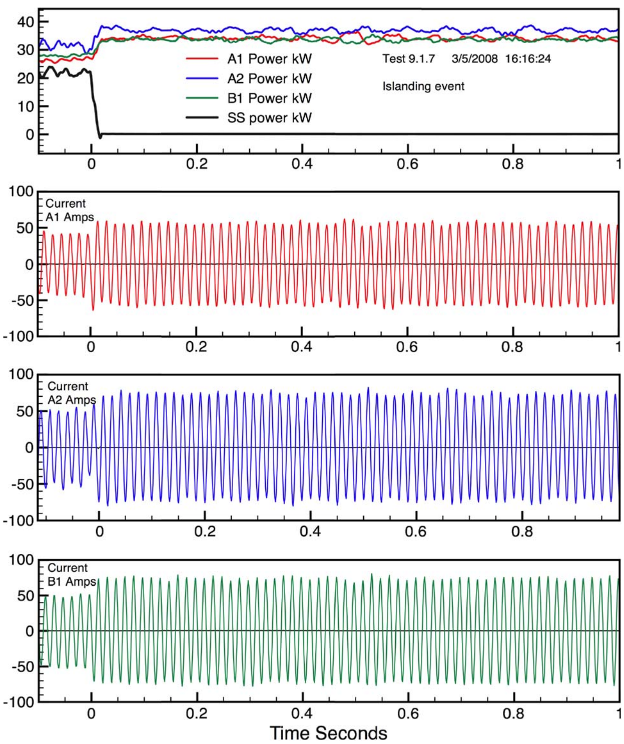


Fig. 6. ***Response of three sources to an islanding event.***

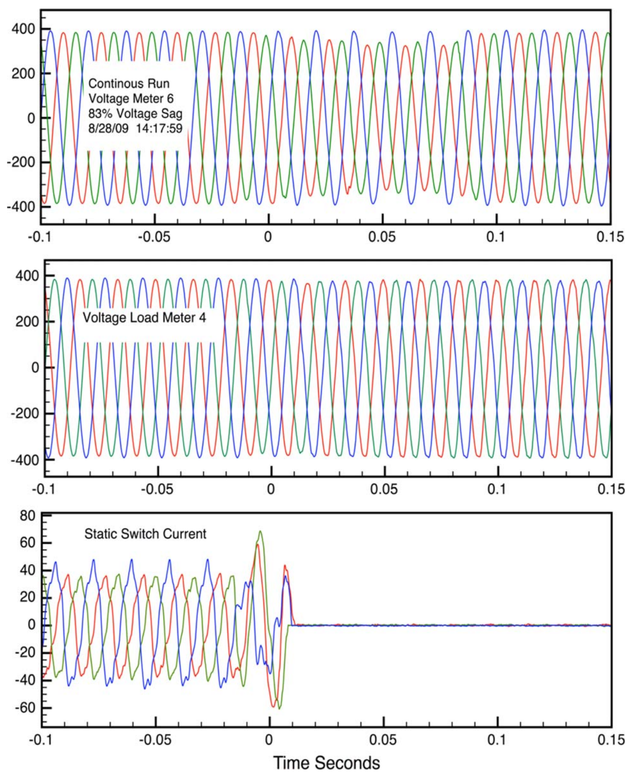


Fig. 7. ***Response to voltage sag.***

demonstrates the dynamics of the sources as they pick up the lost power from the utility. The three other plots in this figure are phase-a currents provided by each of the three sources. The voltage at each source is constant and is not shown. The power sharing demonstrated in this test is inherent in the CERTS concept.

Response to a power quality event is shown in Fig. 7. The event appears to be phase-a to phase-b to ground fault on the utility. The depth of the voltage sag is mild and the duration is short. The cause was either an intermittent fault like a tree contact or a distant fault that was cleared by a downstream recloser. To our knowledge no upstream distribution protection equipment operated to clear this fault. This fault resulted in an 83% voltage sag between phases a and b of the distribution supply for 100 ms, see top voltage plot in Fig. 7. The middle voltage plot shows the high quality of the load's voltage during this event. The response of the static switch shown in the lower current plot indicates an opening time of around one cycle.

The objective of the CERTS Microgrid Laboratory Test Bed project was to demonstrate the ease of integrating distributed energy sources into a microgrid. This includes autonomous sources with *peer-to-peer* and *plug-and-play* functionality. The tests demonstrated stable behavior at critical operations points and the ability to island and reconnect to the grid in an autonomous manner. All tests performed as expected and demonstrated a high level of robustness.

VII. CONCLUSION

An alternative to smart grid concepts using many DER units with a sophisticated command and control systems is to build on microgrid concepts. Using many microgrids in the distribution system is shown to be straightforward. Many "Smart Grid" functions such as improved reliability, high penetration of renewable sources, self-healing, active load control and improved generation efficiencies through the use of waste heat can be implements using coupled microgrids. Microgrid technology has maturing to the point that it is possible to design a full range of microgrid functions from high power quality to utilizing PV sources. Work is need on how to dispatch many microgrids in a distribution system to achieve the desired "Smart Grid" objectives. ■

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