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Microgrids and Distributed Generation

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***Abstract*: Application of individual distributed generators can cause as many problems as it may solve. A better way to realize the emerging potential of distributed generation is to take a system approach which views generation and associated loads as a subsystem or a "microgrid". The sources can operate in parallel to the grid or can operate in island, providing UPS services. The system will disconnect from the utility during large events (i.e. faults, voltage collapses), but may also intentionally disconnect when the quality of power from the grid falls below certain standards. Utilization of waste heat from the sources will increase total efficiency, making the project more financially attractive. University of Wisconsin Laboratory verification of microgrid control concepts are included.**

CE Database subject headings: CHP; distributed generation; intentional islanding; inverters; microgrid; power vs. frequency droop; voltage vs. reactive power droop.

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 generation partially due to the loss of traditional economies of scale. Distributed generation encompasses a wide range of prime mover technologies, such as internal combustion (IC) engines, gas turbines, microturbines, photovoltaic, fuel cells and wind-power. Most emerging technologies such as micro-turbines, photovoltaic, fuel cells and gas internal combustion engines with permanent magnet generator have an inverter to interface with the electrical distribution system. These emerging technologies have lower emissions, have the potential to have lower cost negating traditional economies of scale. The applications include power support at substations, deferral of T&D upgrades and onsite generation.

Penetration of distributed generation across the US has not yet reached significant levels. However that situation is changing rapidly and requires attention to issues related to high penetration of distributed generation within the distribution system. Indiscriminant application of individual distributed generators can cause as many problems as it may solve. A better way to realize the emerging potential of distributed generation is to take a system approach which views generation and associated loads as a subsystem or a "microgrid" (Lasseter 2002a). This approach allows for local control of distributed generation thereby reducing or eliminating the need for central dispatch. During disturbances, the generation and corresponding loads can separate from the distribution system to isolate the microgrid's load from the disturbance (and thereby maintaining high level of service) without harming the transmission grid's integrity. Intentional islanding of generation and loads has the potential to provide a higher local reliability than that provided by the power system as a whole. The size of emerging generation technologies permits generators to be placed optimally in relation to heat loads allow for use of waste heat. Such applications can more than double the overall efficiencies of the systems (Williams 2003).

Most current microgrid implementations combine loads with sources, allow for intentional islanding and try to use the available waste heat. These solutions rely on complex communication and control and are dependent on key components and require extensive site engineering. The objective of this work is to provide these features without a complex control system requiring detailed engineering for each application. Our approach is to provide generator-based controls that enable a plug-and-play model without communication or custom engineering for each site.

Each innovation embodied in the microgrid concept (i.e., intelligent power electronic interfaces, and a single, smart switch for grid disconnect and resynchronization) was created specifically to lower the cost and improve the reliability of smaller-scale distributed generation systems (i.e., systems with installed capacities in the 10's and 100's of kW). The goal of this work is to accelerate realization of the many benefits offered by smaller-scale DG, such as their ability to supply waste heat at the point of need (avoiding extensive thermal distribution networks) or to provide higher power quality to some but not all loads within a facility. From a grid perspective, the microgrid concept is attractive because it recognizes the reality that the nation's distribution system is extensive, old, and will change only very slowly. The microgrid concept enables high penetration of DG without requiring re-design or re-engineering of the distribution system itself**.**

II. EMERGING GENERATION TECHNOLOGIES

Distributed-power applications favor natural-gas technologies principle due to the potential of low air emissions. Diesel-fueled system still dominant in standby and short-run applications, but currently natural gas is better at combining availability, price, and environmental compliance.

Reciprocating engine technology has been driven by economic and environmental pressures for power-density improvements, increased fuel efficiency, and reduced emissions. Emissions of natural-gas engines have improved significantly through better design and control of the combustion process. Advanced lean-burn natural-gas engines produce nitrogen oxide (NOx) levels as low as 50 ppmv, which is an enormous improvement but in most applications still requires the use of exhaust catalysts. Efficiencies are around 35% with a goal of 50%. Unfortunately high efficiency and low emissions are not currently achieved simultaneously.

Microturbin*e*s are an important emerging technology. They are mechanically simple, single shaft devices with air bearings and no lubricants. They are designed to combine the reliability of commercial aircraft auxiliary power units with the low cost of automotive turbochargers. The generator is usually a permanent magnets machine operating at variable speeds (50,000-100,000 rpm). This variable speed operation requires power electronics to interface to the electrical system. Examples include: Capstone's 30-kW and 60- kW systems, and products from European manufacturers Bowman and Turbec. Sophisticated combustion systems, low turbine temperatures and lean fuel-to-air ratios results in NOx emissions of less than 10 ppmv and inherently low-carbon monoxide emissions. Larger gas turbines, reciprocating engines, and reformers all involve higher temperatures that result in much higher NOx production. Microturbines can operate using a number of different fuels including natural-gas and such liquids fuels as gasoline with efficiencies in the 28-30% range.

Fuel cell, which produce electricity from hydrogen and oxygen, emit only water vapor. NOx and CO_2 emissions are associated with the reforming of natural gas or other fuels to produce the fuel cell's hydrogen supply. Fuel cells offer higher efficiency than microturbines with low emissions but are currently expensive. Phosphoric acid cells are commercially available in the 200-kW range, and high temperature solid-oxide and molten-carbonate cells have been demonstrated and are particularly promising for distributed applications. A major development effort by automotive companies has focused on the possibility of using on-board reforming of gasoline or other common fuels to hydrogen, to be used in low temperature proton exchange membrane (PEM) fuel cells. Automotive fuel cells will have a major impact on stationary power if the automotive cost goal of $100/kW is achieved

III. ISSUES AND BENEFITS RELATED TO EMERGING GENERATION TECHNOLOGIES

Control

A basic issue for distributed generation is the technical difficulties related to control of a significant number of microsources. For example for California to meet its DG objective it is possible that this could result in as many as 120,000, 100kW generators on their system. This issue is complex but the call for extensive development in fast sensors and complex control from a central point provides a potential for greater problems. The fundamental problem with a complex control system is that a failure of a control component or a software error will bring the system down. DG needs to be able to respond to events autonomous using only local information. For voltage drops, faults, blackouts etc. the generation needs to switch to island operation using local information. This will require an immediate change in the output power control of the micro-generators as they change from a dispatched power mode to one controlling frequency of the islanded section of network along with load following.

While some emerging control technologies are useful, the traditional power system provides important insights. Key power system concepts can be applied equally well to DG operation. For example the power vs. frequency droop and voltage control used on large utility generators can also provide the same robustness to systems of small DGs. From a communication point of view only the steady state power and voltage needs to be dispatched to optimize the power flow.

The area of major difference from utility generation is the possibility that inverter based DG cannot provide the instantaneous power needs due to lack of a large rotor. In isolated operation, load-tracking problems arise since micro-turbines and fuel cells have slow response to control signals and are inertia-less. A system with clusters of microsources designed to operate in an island mode requires some form of storage to ensure initial energy balance. The necessary storage can come in several forms; batteries or supercapacitors on the DC bus for each micro source; direct connection of AC storage devices (AC batteries; flywheels, etc, including inverters). The CERTS microgrid uses DC storage on each source's DC bus to insure highest levels of reliability. In this situation one additional source (N+1) can insure complete functionality with the loss of any component. This is not the case if there is a single AC storage device for the microgrid.

Operation and investment

The economy of scale favors larger DG units over microsources. For a microsource the cost of the interconnection protection can add as much as 50% to the cost of the system. DG units with a rating of three to five times that of a microsource have a connection cost much less per kWatt since the protection cost remain essentially fixed. The microgrid concept allows for the same cost advantage of large DG units by placing many microsources behind a single interface to the utility.

Using DG to reduce the physical and electrical distance between generation and loads can contribute to improvement in reactive support and enhancement to the voltage profile, removal of distribution and transmission bottlenecks, reduce losses, enhance the possibly of using waste heat and postpone investments in new transmission and large scale generation systems.

Contribution for the reduction of the losses in the European electricity distribution systems will be a major advantage of microsources. Taking Portugal as an example, the losses at the transmission level are about 1.8 to 2 %, while losses at the HV and MV distribution grids are about 4%. This amounts to total losses of about 6% excluding the LV distribution network. In 1999 Portugal's consumption at the LV level was about 18 TWh. This means that with a large integration of microsources, say 20% of the LV load, a reduction of losses of at least, 216 GWh could be achieved. The Portuguese legislation calculates the avoided cost associated with CO_2 pollution as 370g of CO_2/kWh produced by renewable sources. Using the same figures, about 80 kilo tones of avoided annual CO_2 emissions can be obtained in this way. Micro-generation can therefore reduce losses in the European transmission and distribution networks by 2-4%, contributing to a reduction of 20 million tones CO_2 per year in Europe (Lopes 2003).

Optimal location for heating/cooling cogeneration

The use of waste heat through co-generation 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. Since electricity is more readily transported than heat, generation of heat close to the location of the heat load will usually make more sense than generation of heat close to the electrical load.

Most existing power plants, central or distributed, deliver electricity to user sites at an overall fuel-to-electricity efficiency in the range of 28-32%. This represents a loss of around 70% of the primary energy provided to the generator. To reduce this energy loss it is necessary to either increase the fuel-to-electricity efficiency of the generation plant and/or use the waste heat.

Combined power cycles technology can attain efficiencies approaching 60% with ratings in the hundreds of million watts. On the other hand if the waste heat from generators with much lower efficiency (28-32%) can be utilized through heat exchangers, absorption chillers and/or desiccant dehumidification the overall fuel-to-useful energy efficiency can be higher than 80%. Currently Capstone markets a 60kW microturbine using waste heat to heat water. This system has a fuel to useful energy efficiency of 90%.

The size of emerging generation technologies permits generators to be placed optimally in relation to heat loads. The scale of heat production for individual units is small and therefore offers greater flexibility in matching to heat requirements. An ideal system could be constructed from the most economic combination of waste-heat-producing generators and non-waste-heat producing generators so that the combined generation of electricity and heat is optimized. In an extreme example, fuel cells could be placed on every floor of a hospital to meet each floor's hot water needs and provide electricity to local loads.

Power quality/ Power Management/ Reliability

DG has the potential to increase system reliability and power quality due to the decentralization of supply. Increase in reliability levels can be obtained if DG is allowed to operate autonomously in transient conditions, namely when the distribution system operation is disturbed upstream in the grid. In addition, black start functions can minimize down times and aid the re-energization procedure of the bulk distribution system.

Thanks to the redundancy gained in parallel operation, if a grid goes out, the microgrid can continue seamlessly in island mode. Sensitive, mission-critical electronics or processes can be safeguarded from interruption. The expense of secondary onsite power backup is thus reduced or perhaps eliminated, because, in effect, the microgrid and main grid do this already.

In most cases small generation should be part of the building energy management systems. In all likelihood, the DG energy output would be run more cost-effectively with a full range of energy resource optimizing such as peak-shaving, power and waste heat management, centralized load management, price-sensitive fuel selection, compliance with interface contractual terms, emissions monitoring/control and building system controls. The microgrid paradigm provides a general platform to approach power management issues.

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 (Marney 2004). Small generators are better at automatic load following and help avoid large standby charges seen by sites using a single generator. Having multiple DGs on a microgrid makes the chance of all-out failure much less likely, particularly if extra generation is available.

IV. MICROGRID CONCEPT

CERTS Microgrid has two critical components, the static switch and the microsource. 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 insuring a transient free operation without having to match frequency and phase angles at the connection point. Each microsource can seamlessly balance the power on the islanded Microgrid using a power vs. frequency droop controller. This frequency droop also insures that the Microgrid frequency is different from the grid to facilitate reconnection to the utility.

Basic microgrid architecture is shown in Figure 1. This consists of a group of radial feeders, which could be part of a distribution system or a building's electrical system. There is a single point of connection to the utility called point of common coupling (Lasseter 2002b). Some feeders, (Feeders A-C) have sensitive loads, which require local generation. The non-critical load feeders do not have any local generation. Feeders A-C can island from the grid using the static switch that can separate in less than a cycle (Zang 2003). In this example there are four microsources at nodes 8, 11, 16 and 22, which control the operation using only local voltages and currents measurements.

When there is a problem with the utility supply the static switch will open, isolating the sensitive loads from the power grid. Non-sensitive loads (feeder D) rides through the event. It is assumed that there is sufficient generation on feeders A, B, and C to meet the loads' on theses feeders. When the microgrid is grid-connected power from the local generation can be directed to the non-sensitive loads.

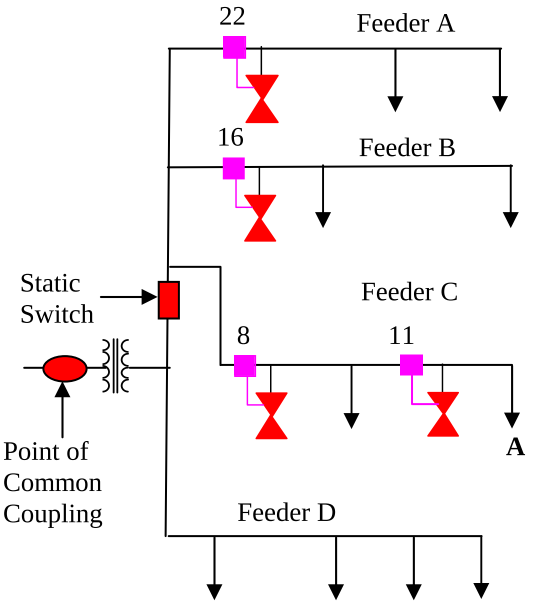


Figure. 1. Microgrid Architecture Diagram.

To achieve this we promote autonomous control in a peer-to-peer and plug-and-play operation model for each component of the microgrid. The peer-to-peer concept insures that there are no components, such as a master controller or central storage unit that is critical for operation of the microgrid. 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. Plug-and-play implies that a unit can be placed at any point on the electrical system without re-engineering the controls. 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.

Unit Power Control Configuration

In this configuration each DG regulates the voltage magnitude at the connection point and the power that the source is injecting, P. This is the power that flows from the microsource as shown in Figure 1. With this configuration, if a load increases anywhere in the microgrid, the extra power comes from the grid, since every unit regulates to constant output power. This configuration fits CHP applications because production of power depends on the heat demand. Electricity production makes sense only at high efficiencies, which can only be obtained only when the waste heat is utilized. When the system islands the local power vs. frequency droop function insures that the power is balanced within the island.

Feeder Flow Control Configuration

In this configuration, each DG regulates the voltage magnitude at the connection point and the power that is flowing in the feeder at the points 8, 11, 16 and 22 in Figure 1. With this configuration extra load demands are picked up by the DG, showing a constant load to the utility grid. In this case, the microgrid becomes a true dispatchable load as seen from the utility side, allowing for demand-side management arrangements. Again, when the system islands the local feeder flow vs. frequency droop function insures that the power is balanced.

Mixed Control Configuration

In this configuration, some of the DGs regulate their output power, P, while some others regulate the feeder power flow. The same unit could control either power or flow depending on the needs. This configuration could potentially offer the best of both worlds: some units operating at peak efficiency recuperating waste heat, some other units ensuring that the power flow from the grid stays constant under changing load conditions within the microgrid.

V. MICROSOURCE CONTROL

Microsource controls need to insure that: new microsources can be added to the system without modification of existing equipment, setpoints can be independently chosen, the microgrid can connect to or isolate itself from the grid in a rapid and seamless fashion, reactive and active power can be independently controlled, and can meet the dynamic needs of the loads.

Each microsource controller must autonomously respond effectively to system changes without requiring data from the loads, the static switch or other sources. The same applies to the static switch. The basic controller uses a feed back control on power and voltage. The controls use real time values for P, Q, frequency and the AC voltage to generate the desired voltage magnitude and angle at the inverter terminals using droop concepts. Operating the inverter as a voltage behind an impedance results in real power being proportional to the phase angle across the coupling inductor and the injected reactive power is proportional to the magnitude of the inverter's output voltage.

Voltage vs. Reactive Power (Q) Droop

Integration of large numbers of microsources into a Microgrid is not possible with basic unity power factor controls. Voltage regulation is necessary for local reliability and stability. Without local voltage control, systems with high penetrations of microsources could experience voltage and/or reactive power oscillations. Voltage control must also insure that there are no large circulating reactive currents between sources. With small errors in voltage set points, the circulating current can exceed the ratings of the microsources. This situation requires a voltage vs. reactive power droop controller so that, as the reactive power generated by the microsource becomes more capacitive, the local voltage set point is reduced. Conversely, as Q becomes more inductive, the voltage set point is increased.

Power vs. Frequency Droop

When the microgrid is connected to the grid, loads receive power both from the grid and from local microsources, depending on the customer's situation. If the grid power is lost because of IEEE 1547 events, voltage sags, faults, blackouts, etc., the Microgrid can autonomously transfer to island operation.

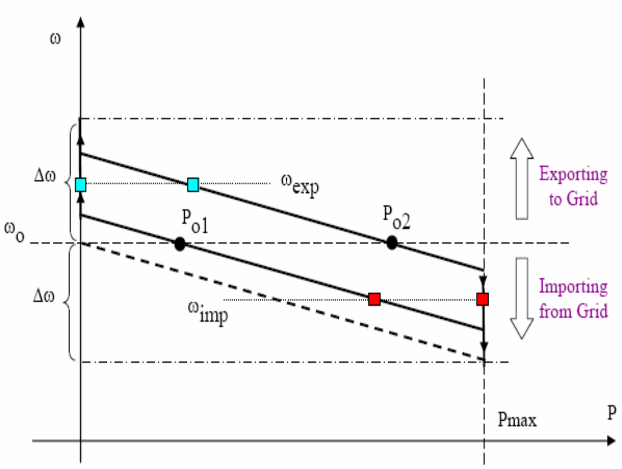


Figure. 2. Power vs. Frequency droop

When regulating the output power, each source has a constant negative slope droop on the P,ω plane where P is output power and ω is frequency in radians per second. Figure 2 shows that the slope is chosen by allowing the frequency to drop by a given amount, Δω, as the power spans from zero to Pmax, dashed line. Figure 2 also shows the power setpoints Po1 and Po2 for two units. This is the amount of power injected by each source when connected to the grid, at system frequency. If the system transfers to island when importing from the grid, then the generation needs to increase power to balance power in the island. The new operating point will be at a frequency that is 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 with unit 1 at its zero power point.

Figure. 4. Steady States Characteristics for UW Test.

The characteristics shown on Figure 2 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 where the steady state points are constrained to come to rest, but during dynamics the trajectory will deviate from the characteristic.

VI. UW-MICROGRID

The CERTS microgrid concept has been implemented in a proof-of-concept hardware setup at the University of Wisconsin-Madison. This Microgrid includes two sources, five sets of three phase loads and a static switch to allow connection to the grid. Figure 3 shows the component layout. Notice the overall 100 yd cable between the sources to better capture the voltage drops that normally exist on feeders (Venakataramanan 2002). The off-the-shelf inverter's control card has been replaced with a custom made board that allows interface with a Digital Signal Processor (DSP). The control is digitally implemented in the DSP to drive the behavior of the inverter. The measurement of the currents flowing on the local feeder is used in the feeder flow control option. Notice that the measure of the currents injected by the unit is needed also during feeder flow control since it is used to calculate the reactive power, Q, and the active power, P, to enforce its limits.

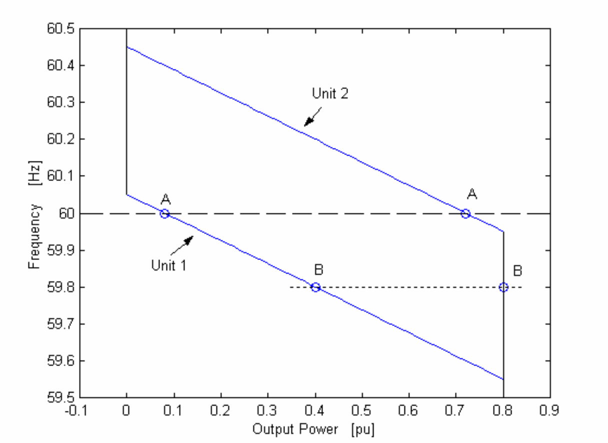
VII. CASE STUDY

This section will display some of the hardware results obtained at the UW-Microgrid testbed. Figure 3 shows the layout that is used on both of these two tests. Each of the loads is 0.3 pu, and load L2 is off all the time. Total load is 1.2 pu. The units have a power range from zero (idle), to 0.8 pu (Pmax = 15 kW). These results are directly coming off the DSP memory core where quantities can only be represented with values between –1,+1. To ensure that small amouts of overshoot are measurable, then the value corresponding to maximum power is chosen to be 0.8 pu.

Test: Transfer to Island, Control of P_1 and P_2

In the experiment, shown on Figure 4, the system transfers to island when both units are regulating output power. When connected to the grid (steady state "A") the system is importing power. In the steady state during island both units feed the total load, "B". Unit 2 is sitting on Pmax output, while unit 1 provides the needed load power. Figure 5 shows the actual traces of this test from both units. The active power of unit 2 overshoots maximum but then the control backs off the generation: then unit 1 increases its output to meet the loads. Feeder flows are shown but are not used by the control. Voltage magnitude is unchanged and the frequency drops in both machines following the event.

Figure. 4. Steady States Characteristics for UW Test.



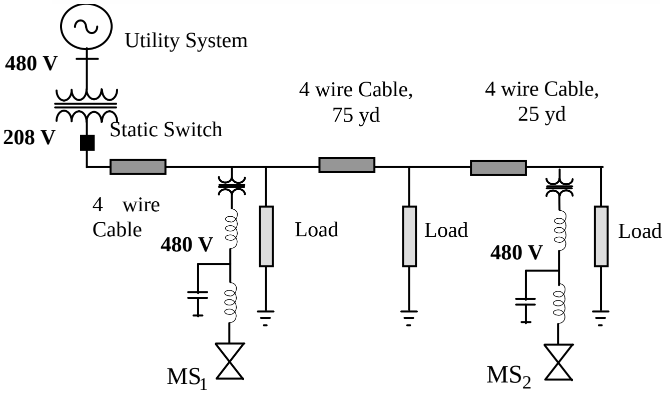


Figure. 3. UW-Microgrid Circuit

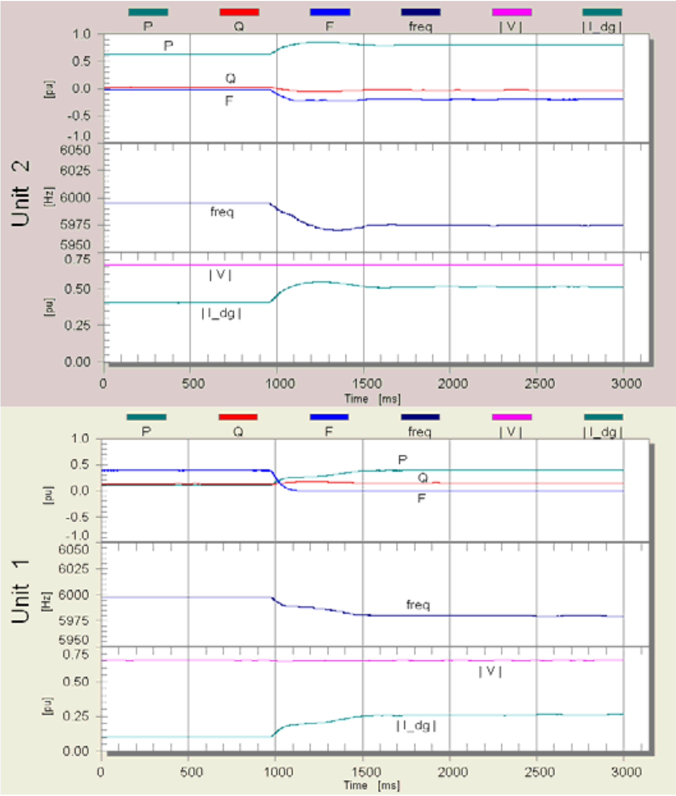


Figure. 5. Dynamics: P, Q, F, Frequency, Voltage Magnitude, Current Magnitude, for Unit 1 and 2. 500ms/div.

VIII. CONCLUSION

The work on the microgrid has progressed well. The work at Wisconsin demonstrates the effectiveness of local control of distributed generation thereby reducing or eliminating the need for central dispatch. During disturbances, the generation and corresponding loads can separate from the distribution system to isolate the microgrid's load from the disturbance (and thereby maintaining high level of service) without harming the transmission grid's integrity. Intentional islanding of generation and loads provide a higher local reliability than that provided by the power system as a whole. The size of emerging generation technologies permits generators to be placed optimally in relation to heat loads allow for use of waste heat. Such applications can more than double the overall efficiencies of the systems. Currently with support from California Energy Commission the design and construction of a full scale Microgrid is in progress. This Microgrid will be constructed and tested at American Electric and Power site starting spring 2006. This test site will include three 60kW microsources from Tecogen with inverter interface.

IX. ACKNOWLEDGEMENTS

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