Autonomous Control of Microgrids

Paolo Piagi , *Member, IEEE,* Robert H. Lasseter, *Fellow, IEEE*

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. Laboratory verification of the Consortium for Electric Reliability Technology Solutions (CERTS) microgrid control concepts are included.**

Index Terms--**CHP, distributed generation, intentional islanding, inverters, microgrid, power vs. frequency droop, voltage droop,**

I. INTRODUCTION

Distributed generation (DG) encompasses a wide range of prime mover technologies, such as internal combustion (IC) engines, gas turbines, microturbines, photovoltaic, fuel cells and wind-power.

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. 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 CERTS microgrid concept is an advanced approach for enabling integration of, in principle, an unlimited quantity of distributed energy resources into the electricity grid. The microgrid concept is driven by two fundamental principles:[1]

1) A *systems* perspective is necessary for customers, utilities, and society to capture the full benefits of integrating distributed energy resources into an energy system; and 2) The *business case* for accelerating adoption of these advanced concepts will be driven, primarily, by lowering the first cost and enhancing the value of microgrids [1].

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**.**

During disturbances, the generation and corresponding loads can autonomously 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 smaller size of emerging generation technologies permits generators to be placed optimally in relation to heat loads allowing for use of waste heat. Such applications can more than double the overall efficiencies of the systems [2].

II. EMERGING GENERATION TECHNOLOGIES

In terms of the currently available technologies, the microsources can include fuel cells, renewable generation, as wind turbines or PV systems, microturbines and inverter based internal combustion generators. One of the most promising applications of this new concept corresponds to the combined heat and power – CHP – applications leading to an increase of the overall energy effectiveness of the whole system.

Most emerging technologies such as micro-turbines, photovoltaic, fuel cells and natural gas fired internal combustion engines with permanent magnet generator require an inverter to interface with the electrical distribution system.

Photovoltaic and wind-power are important renewable technologies that require an inverter to interface with the electrical distribution system. The major issue with these technologies is the nature of the generation. The availability of their energy source is driven by weather, not the loads of the systems. These technologies can be labeled as intermittent and ideally they should be operated at maximum output. Intermittent sources can be used in the CERTS microgrid as a "negative load", but not as a dispatchable source.

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.

We believe that 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 [3].

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 [4]. 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.

Under present conditions, the ideal positioning of cooling-heating-and-power cogeneration is often hindered by utility objections, whether legitimate or obstructionist. In a microgrid array, neither obstacle would remain. Utilities no longer have issues to raise regarding hazards. Consequently, DGs don't all have to be placed together in tandem in the basement anymore but can be located where the heat loads are needed in the building. CHP plants can be sited optimally for heat utilization. A microgrid becomes, in effect, a little utility system with very *pro*-CHP policies rather than objections.

The small size of emerging generation technologies permits generators to be placed optimally in relation to heat or cooling loads. The scale of heat production for individual units is small and therefore offers greater flexibility in matching the heat requirements.

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 [5], in terms of energy source security, that multiple small generators are more efficient than relying on a single large one for lowering electric bills. 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 [6]. 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 [7]. 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.
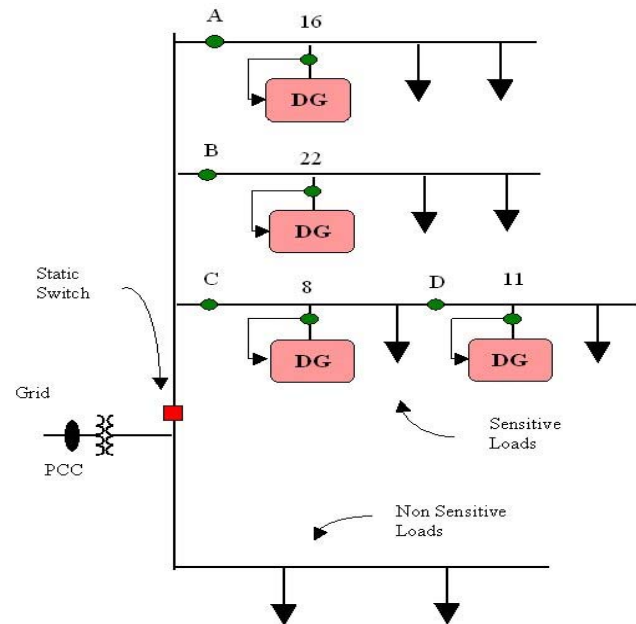

Fig. 1. Microgrid Architecture Diagram.

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 ride through the event. It is assumed that there is sufficient generation to meet the loads' demand.

When the microgrid is grid-connected power from the local generation can be directed to the non-sensitive loads.

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 A, B, C and D 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 block diagram of the control is shown in Figure 2. The blocks on the left calculate the real time values for P, Q and the voltage magnitude. The two droops are implemented in separate blocks. The control generates the desired voltage magnitude and angle at the inverter terminals. The gate pulse generator is responsible to issue the correct firing pulses to the power electronics inside the inverter to track the control's requests. Operating the inverter as a voltage behind an impedance results in $P \approx \delta$ and $Q \approx |V|$
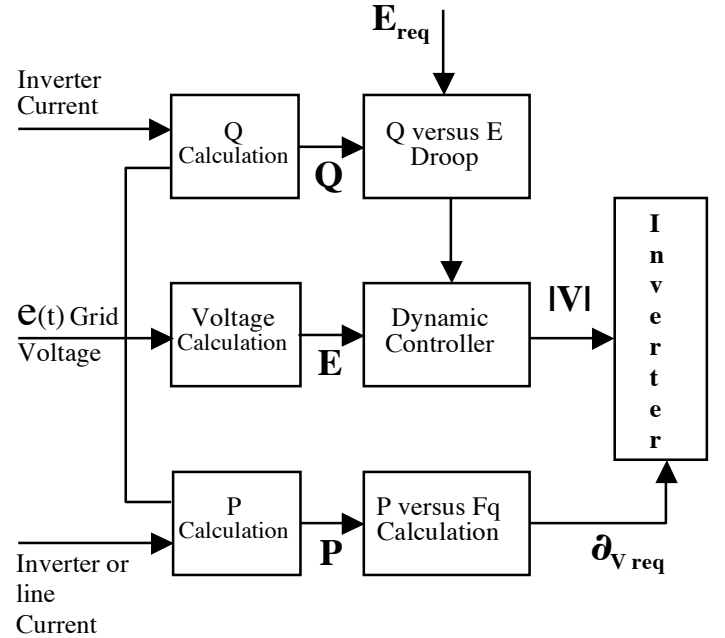

Fig. 2. Microsource Controller

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 droops, faults, blackouts, etc., the Microgrid can autonomously transfer to island operation.

When regulating the output power, each source has a constant negative slope droop on the P,ω plane. Figure 3 shows that the slope is chosen by allowing the frequency to drop by a given amount, $\Delta\omega$, as the power spans from zero to Pmax, dashed line. Figure 3 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.

The characteristics shown on Figure 3 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.

$$m = -\frac{\Delta\omega}{P_{max}}$$
$$\omega_i = \omega_o - m\left(P_{o,i} - P_i\right)$$

Flow vs. Frequency Droop

When regulating the feeder flow F, each source has a positive slope on the F, ω plane, Figure 5. This fixed value has the same magnitude that was used in the P, ω plane, but with a reversed sign. When regulating P the relative location of loads and source is irrelevant but when regulating F this factor becomes important.
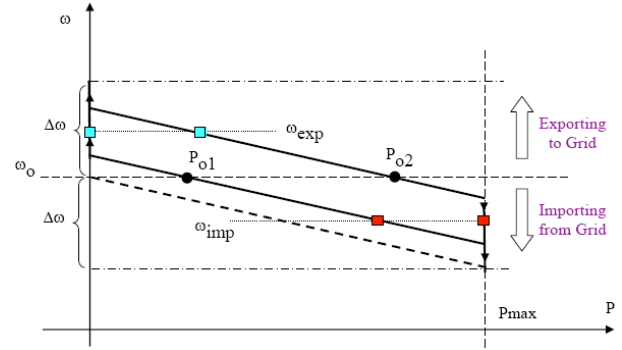

Fig. 3. Active Power vs. Frequency Droop.

Figure 4 shows two possible microgrid configurations: series and parallel. Figure 5 shows the setpoints F_{01} and F_{02} (circles) for the two units when connected to the utility system. When in series configuration, F_{01} is the grid flow. The microgrid is exporting power to the grid, since flow is negative. When the system transfers to island, the flow reaches zero and the frequency increases (squares).
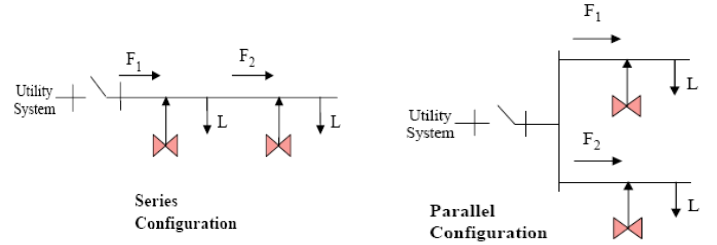

Fig. 4. Microgrid Configurations with Two Sources

In the parallel configuration, the grid flow is the algebraic sum of the two flows. Since $|F_{02}| > |F_{01}|$ the microgrid is importing power from the grid. Figure 5 shows that in island mode $F_{01} = -F_{02}$ and the frequency is reduced (triangles).
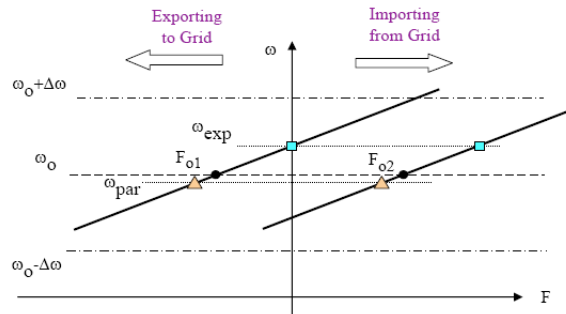

Fig. 5. Feeder Flow vs. Frequency Droop.

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 6 shows the component layout. Notice the overall 100 yd cable between the sources to better capture the voltage drops that normally exist on feeders [8].
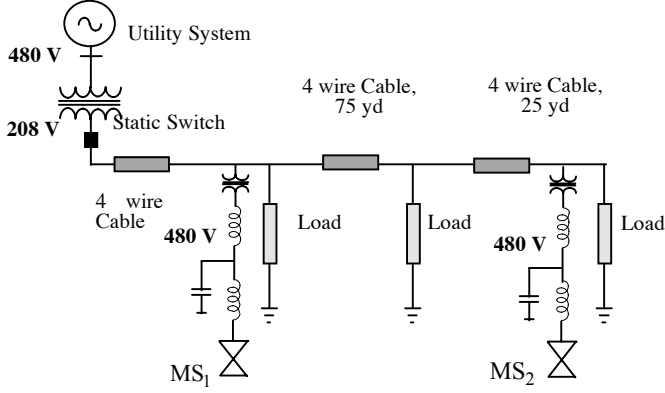

Fig. 6. UW−Microgrid Diagram

Figure 7 shows the details of each source. The power is provided by a DC voltage source. This provides an excellent emulation of a microturbines and fuel cell systems with storage on dc bus. At the AC terminals of the inverter there is an LC filter to trap the components at the switching frequency. The transformer and inductor are sized to insure that the voltage angle across the inductance is 10° at full power.

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.
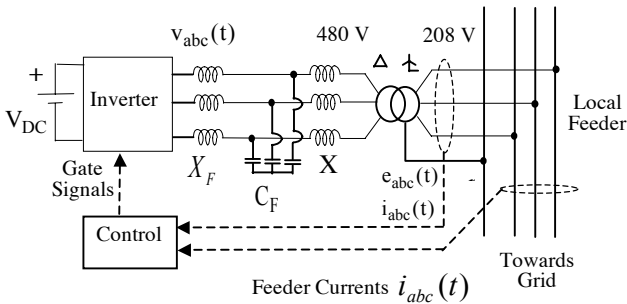

Fig. 7. Microsource Diagram.

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 6 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-1: Transfer to Island, Control of P_1 and P_2

In the first experiment, shown on Figure 8, 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 9 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.
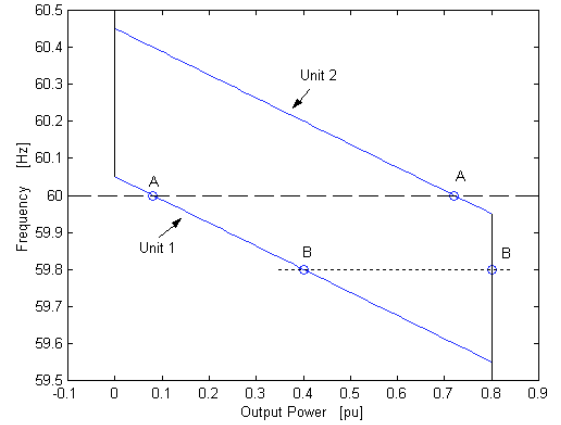

Fig. 8. Test-1 Steady States.

Test-2: Transfer to Island, Control of F_1 and P_2

The setup of the second experiment uses the same amount of loads used in the first experiment, Figure 6. This case shows a transfer to island with a mixed system, where unit 1 regulates feeder flow F, and unit 2 regulates output power, P. The flow command at unit 1 corresponds to the flow from the grid: the system is importing power from the utility (steady state "A" on Figure 10).
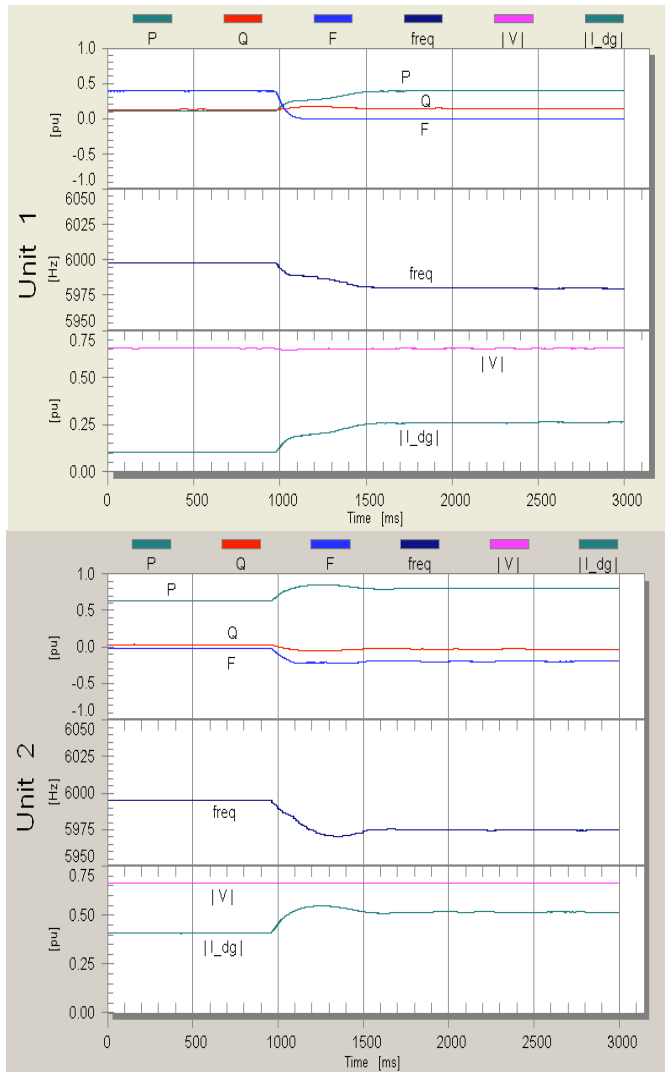
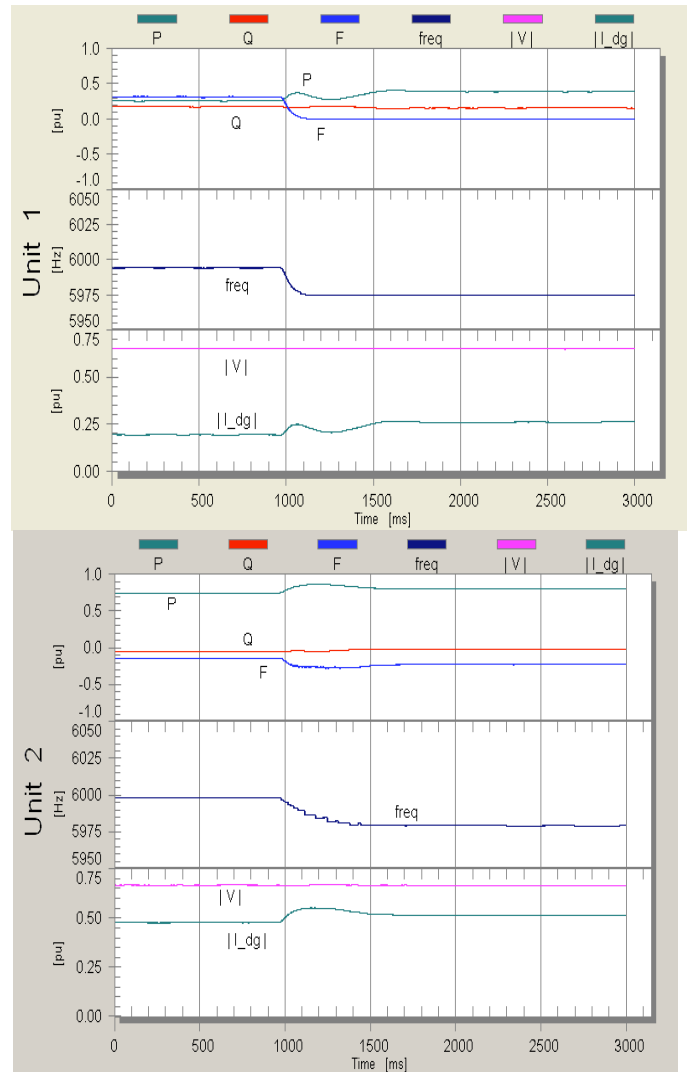Fig. 9. Test-1Dynamics: P, Q, F, frequency, Voltage Magnitude, Current Magnitude, for Unit 1 and 2. 500ms/div.

Fig. 11. Test-2 Dynamics: P, Q, F, frequency, Voltage Magnitude, Current Magnitude, for Unit 1 and 2. 500ms/div
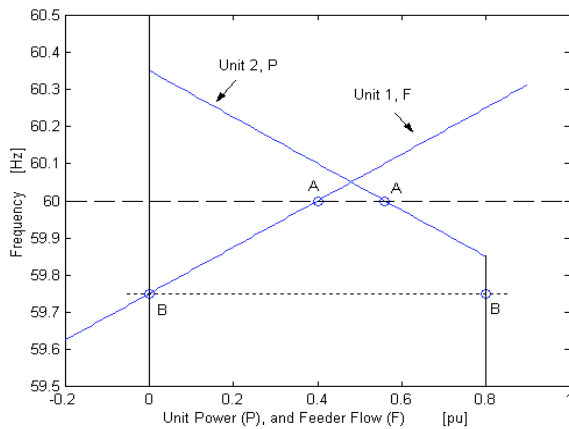
Figure 11 shows the traces recording the measures for both units during the experiment. The flow at unit 1 goes to zero, while the output power of unit 2 overshoots maximum. As the control backs off this source, unit 1 picks up the power, while maintaining its flow (the grid flow) to zero. In this case the voltage magnitude remains fixed during the event and the frequency drops in both units. After the transition to island, the flow at unit 1 is zero and unit 2 is operating at maximum output power, (steady state "B").

Fig. 10. Test-2 Steady States.

VIII. CONCLUSION

The work on the microgrid has progressed well. Currently with support from California Energy Commission in conjunction with CERTS we are starting the design and construction of a full scale Microgrid. This Microgrid will be constructed and tested at a utility site. This test site will include three 60kW microsourcess.

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Robert H. Lasseter (F92) received the Ph.D. in Physics from the University of Pennsylvania, Philadelphia in 1971. He was a Consulting Engineer at General Electric Co. until he joined the University of Wisconsin-Madison in 1980. His research interests focus on the application of power electronics to utility systems and technical issues which arise from the restructuring of the power utility system. This work includes interfacing micro-turbines and fuel cells to the distribution grid, control of power systems through FACTS controllers, use of power electronics in distribution systems and harmonic interactions in power electronic circuits. Professor Lasseter is a Fellow of IEEE, an expert advisor to CIGRE SC14.

Paolo Piagi obtained his B.S. in Electrical Engineering at the Polytechnic of Turin, in Italy. He recently obtained his Ph.D. in EE at the University of Wisconsin-Madison under the supervision of Professor R.H. Lasseter and is currently holding a post-doc researching position under the same advisor. Paolo developed a control for inverter-based distributed resources and then implemented his design on DSP. He has been involved in testing it in a lab scale microgrid and is currently involved on the project development aspect, helping industry implement the control on a real world prototype.